Autonomous Socially Assistive Robotics in Pediatric Clinical Practice

by

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Published and Submitted Content

All the contributions of this doctoral thesis have been published in journals, conferences and workshops. This section enumerates the involved publications and relates them to the main chapters and sections, specifying the way of inclusion. *Note: the material from these sources included in this thesis is not singled out with typographic means and references.*

INDEXED JOURNALS:

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Other Research Merits

This section lists the rest of publications that, although out of the scope of this thesis, are related works carried out in parallel. Also included are the entrepreneurship awards and accolades received by NAOTherapist, a prototype developed in this thesis.

OTHER PUBLICATIONS:

- (2020) N. Fitter, R. Funke, JC. Pulido, M. Matarić and Beth Smith. **Predicting Infant Developmental Outcomes from Day-Long Inertial Motion Recordings**. *IEEE T. on Neural Systems and Rehabilitation Engineering.*
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  url: https://arxiv.org/pdf/1807.02617.pdf

- **Publication #12:**
  (2019, September) W. Deng, M. Rosales, N. S. Bradley, JC. Pulido, M. Matarić and Beth A. Smith. **Toward an Understanding of Infant Behavior Changes During Contingent Learning with a Socially Assistive Humanoid Robot**. *IEEE International Conference on Development and Learning and on Epigenetic Robotics. Oslo, (Norway).*
  url: https://robotics.usc.edu/publications/downloads/pub/1058/

- **Publication #13:**
  (2018, August) D. Goodfellow, R. Zhi, R. Funke, JC. Pulido, M. Matarić and Beth A. Smith. **Classifying Infant Motor Development using Day Long Movement Data from Wearable Sensors**. *2018 KDD Workshop in Machine Learning in Healthcare and Medicine, London.*
  url: https://arxiv.org/pdf/1807.02617.pdf

- **Publication #14:**
  (2017, November) D. Voilmy, C. Suárez, A. Romero-Garces, C. Reuther, JC. Pulido, R. Marfil, L. J Manso, K. Lan Hing Ting, A. Iglesias, JC. Gonzalez, J. Garcia, A.

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- **Publication #16:**
(2016, June) A. Bandera, JP. Bandera, P. Bustos, L. V. Calderita, Á. Dueñas, F. Fernández, R. Fuentetaja, Á. García-Olaya, J. García, JC. González, A. Iglesias, L. Manso, R. Marfil, JC. Pulido, C. Reuther, A. Romero-Garcés and C. Suárez. **CLARC: a Robotic Architecture for Comprehensive Geriatric Assessment**. *17th Workshop of Physical Agents (WAF), pp. 1-8, Málaga (Spain).*
url: 2016-Clarc-robotic-architecture.pdf

- **Publication #17:**
(2015, November) M. Turp, JC. Pulido, JC. González and F. Fernández. **Playing with Robots: An Interactive Simon Game**. *16th Conference of the Spanish Association for Artificial Intelligence (CAEPIA), RSIM workshop, pp. 1085-1095, Albacete (Spain).*
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- **Publication #18:**
(2015, October) A. Martín, JC. González, JC. Pulido, A. G.-Olaya, F. Fernández and C. Suárez. M. Turp, JC. Pulido, JC. González and F. Fernández **Therapy Monitoring and Patient Evaluation with Social Robots**. *3rd Workshop on ICTs for improving Patients Rehabilitation Research Techniques (REHAB), pp. 152-155, Lisbon (Portugal).*
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AWARDS & ACCOLADES:

The NAOTherapist project was built based on part of the results of this thesis. This project offers physical-cognitive rehabilitation sessions with an autonomous social robot for pediatric patients. The following list enumerates the awards and accolades we have achieved in several solidarity and entrepreneurship programs:

- 2019: NAOTherapist was selected to participate in *The Collider* entrepreneurship program of the *World Mobile Congress*, rewarded with a grant of 50,000 euros.
- 2019: NAOTherapist was selected to participate in the *CaixaImpulse* entrepreneurship program from *La Caixa*, rewarded with a grant ranging from 70,000 to 100,000 euros.
- 2017: Winner of the first prize of the 6th edition of the act *Implicados y solidarios* organized by *Bankinter*, given to the *DACER foundation* for the NAOTherapist project, rewarded with of 13,000 euros.
- 2017: Winner of the *e-Health 2017* award from the *Asociación de Investigadores en eSalud (AIES)* and *COM Salud*, celebrated on the 2nd *e-Health National Congress* for NAOTherapist as the best project in the robotics category.
- 2017: *National Geographic* tells the story of the NAOTherapist developers in an exclusive documentary of 30 minutes into the *Hacia un mundo mejor* television series. Chapter 1: *Terapia amistosa*.[1]
- 2016: Winner of the third prize in the final national round of the 7th edition of the *Yuzz Jóvenes con ideas* entrepreneurship program for the NAOTherapist project, rewarded with 10,000 euros.
- 2016: Winner of the *Universidad Carlos III de Madrid (UC3M) center* of the 7th edition of the *Yuzz Jóvenes con ideas* entrepreneurship program for the NAOTherapist project, rewarded with a trip to Silicon Valley (California, USA) and the participation in the final national round of the competition.

[1] *National Geographic* documentary: https://youtu.be/f89X_F-09tQ

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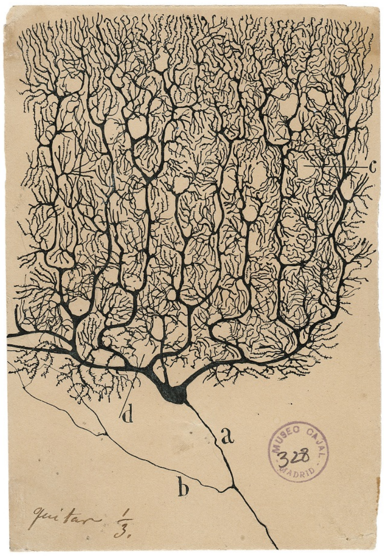
Neurorehabilitation, Socially Assistive Robotics, Artificial Intelligence, Gamification.

"Every man if he so desires
becomes sculptor of his own brain."
- Ramón y Cajal -



Abstract

The development of new devices to support neurological recovery is a current challenge for clinical professionals and engineers [Tapus et al. 2007b]. Particularly, in the last decade, robotic applications have demonstrated their great potential as novel approaches [Drużbicki et al. 2013]. Socially Assistive Robotics refers to those robots that provide assistance to human beings through social interaction. This technology is particularly interesting in healthcare domains since it is able to elicit more favorable responses to the treatment [Okamura et al. 2010]. All these approaches start from the same hypothesis: the interaction provided by a social robot helps patients to get engaged with the treatment, in addition to automatic data gathering and reporting, helping to relieve the workload of healthcare professionals while reducing the socio-economic costs.

Under this context, this thesis arises from four foundations: neurorehabilitation, socially assistive robotics, gamification and artificial intelligence. The integration of these fundamentals aims to design a child-robot interaction framework to enhance the pediatric clinical practice. The designed framework is provided with an intelligent system, so that no engineer is required either to control the interaction or to adapt the system. During the development of this thesis the framework has been used and evaluated in two different tasks: pediatric rehabilitation (NAOTherapist) and motion encouragement. Being the first one the central application of the presented work. In NAOTherapist, child-robot sessions are composed of playful immersive activities based on reward and positive reinforcement to improve motivation and, therefore, adherence to treatments. The ultimate goal is to demonstrate the feasibility of this framework in real healthcare settings, so a user-centered prototyping is proposed by involving the user during each development phase. A prototype was initially evaluated with more than 120 of typically developing children, obtaining a generalized high degree of active engagement [Pulido et al. 2017]. After that, three evaluation scenarios exposed the platform to the real practice: a first contact to get closer to the target individual, a long-term experience to determine personalization needs [Pulido et al. 2019], and an intensive intervention to evaluate the motivation and adherence to treatment. About 20 pediatric patients participated in the studies with very promising results. In all cases, the sessions with the robot provided a greater motivation compared to the conventional treatment, getting patients to exceed the objectives marked by the experts. Positive reinforcement and rewarding the patient were fundamental aspects to maintain motivation. The robot autonomy was also a key point, so making the robot taking its own decisions improved the perception of social entity. The interviewed relatives detected functional and self-esteem enhancements in their children, and experts confirmed the system utility and usability for application in pediatrics.

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Chapter 1

Introduction

For more than 50 years, robotics research has linked its activity in the search for solutions to certain technical demands. The evolution of application fields and their sophistication have been dominated by human needs [Garcia et al. 2007]. In the early 1960s, the first robots began to intervene in industrial manufacturing processes assuming the risks that certain tasks entailed for the operators. Currently, the field of application is very widespread, responding to the new needs of the market. Robots begin to appear in construction, agriculture, cleaning, exploration and so on. In addition, anticipating the global aging of society, new lines of research are emerging that seek to cover certain social needs [Pino et al. 2015]. The current technological era favors interactions between humans and robots, encouraging in many cases better responses from users in healthcare settings [Lee et al. 2012]. These technological phenomena have been consolidated in many areas of the society. In some aspects, robots are still a controversial technology, although it is undeniable that they also present great advantages for human beings.

This thesis arises from the field of socially assistive robotics. This concept was born as a result of these society demands, and refers to all robots that provide assistance to people through social interaction [Feil-Seifer et al. 2005a]. This assistive technology is beginning to spread and to actively participate in clinical interventions, typically in pediatrics, where it has proven to be very promising [Dawe et al. 2019]. Social robotics has unique characteristics that could cover the needs of the pediatric patients [Kuo et al. 2012]. These robots can assist children to better manage their illnesses and treatments through positive reinforcement, training, education and encouragement to bring healthy habits. In situations of isolation or hospitalization, these platforms can offer companionship and comfort to patients that is fundamental for a positive attitude in recovery [Breazeal 2011]. However, socially assistive robotics is a novel multidisciplinary research line at an early stage of development and evaluation, and with a large number of challenges ahead [Tapus et al. 2007a]. Contributing to the evolution of knowledge requires efforts to understand the foundations of the different disciplines that it encompasses. Section 1.1 continues explaining the motivation of using social robots in healthcare interventions. After that, Section 1.2 establishes the fundamentals of this thesis and Section 1.3 defines the objectives.

1.1 Motivation

Social robots are designed to establish interpersonal relationships like those of human beings [Breazeal 2004], based on social characteristics such as emotions, verbal and non-verbal communication, gaze, gestures, personality and ability to develop social competences. In other words, the way they interact is consistent with the psychosocial principles of human beings. This technology is particularly interesting in health domains since it is able to involve people along social and emotional dimensions, eliciting more favorable responses to the treatment [Okamura et al. 2010]. A socially assistive robot has the potential to improve the services offered by healthcare providers saving costs and, at the same time, providing a satisfactory and personalized experience.

A significant trend is the development of devices and robotic applications that offer support to the elderly. By the year 2050, the latest estimate indicates that there will be an increase of 100% in the number of people over 80 years old over all the inhabitants of the planet [DESA 2015]. This trend towards an aging population will increase the prevalence of injuries, disorders and diseases, as well as the demand for health and home care. A large number of opportunities are opened for the introduction of social robotics in the context of caring for the elderly, highlighting their ability to educate, facilitate communication and the social connection of the elderly with their relatives [Breazeal 2011]. Researchers have shown that while elders interact with a social robot, they have the perception of not being judged, which in many cases makes them behave and answer freely, reducing the levels of stress and anxiety that may be present in many ambulatory situations [Bickmore et al. 2005, Lee et al. 2010].

Another very important trend revolves around the neurodevelopmental processes in pediatrics. Neurorehabilitation treatments focus on the recovery of damaged neuronal areas and muscles by the repetitive practice of certain motor or cognitive activities [Dobkin 2004]. The need towards novel rehabilitation approaches arises from the lack of commitment of patients with the treatment, negatively affecting their quality of life [Colombo et al. 2007]. Therapists have detected communication problems and lack of motivation as the two main problems. Patients with cognitive disorders may present difficulties to communicate with their therapists, which results in a lack of complicity to perform any activity [Kanner et al. 1943]. In this line, numerous works have demonstrated the effectiveness of using a social robotic platform that breaks these barriers [Dawe et al. 2019]. These works state that a robot-assisted therapy can stimulate better responses from pediatric patients [Lee et al. 2012, Miyamoto et al. 2005]. The main advantage for the therapist is the use of the social robot as a communication interface with the patient. The success of these approaches is given by the emotional bounds between the patient and the robot, improving the continuity with the treatment [Mataric et al. 2007, Dehkordi et al. 2015, Wainer et al. 2013, Boccanfuso et al. 2011, Kozima et al. 2008]. The benefits of robotics in this kind of treatments are very significant. Active robot collaboration in rehabilitation sessions is a labour-saving factor and allows to automatize the therapy supervision and monitoring [Mataric et al. 2007]. There is a whole line of research among the benefits of these techniques in therapies [Drużbicki et al. 2013, Ros et al. 2011, Borggraefe et al. 2010].

In the area of rehabilitation, social robots have demonstrated improvements in the commitment and positive effects on the motivation of several groups of patients who suffer from physical impairments (cerebral palsy, stroke) [Fasola et al. 2010, Tapus et al. 2009] or cognitive disorders (autism, dementia) [Cabibihan et al. 2013, Šabanović et al. 2013]. They offer novel rehabilitation tools to relieve the workload of professionals while reducing the socio-economic costs of therapy sessions. To achieve this result, social robots should be designed taking into account several key challenges: the appearance of the robot, the fulfillment of the clinical objectives through social interaction and the autonomy to carry out the sessions, being able to react to unexpected situations [Tapus et al. 2007b].

The interaction with a social robot is very attractive, but it does not guarantee a long-term engagement in patients due to the prolonged exposure of the platform. It is possible that, over time, patients become accustomed and may lose interest in the robot. People are currently exposed to very complex and sophisticated devices, so that the interest may be easily lost when the limits of the robot's responsiveness are discovered [Belpaeme et al. 2013b]. Avoiding this situation is a great challenge for the scientific community [Tapus et al. 2007b]. Autonomy is still an open issue in the development of assistive robotic platforms to guarantee a successful interaction

[Dawe et al. 2019]. Numerous shortcomings have been identified in relation to the sophistication of robotic control systems and decision making. Most approaches lack complete autonomy or propose solutions based on teleoperation, since it allows to make very rapid developments with evaluations whose interaction is controlled by a human [Belpaeme et al. 2013a]. However, the need to teleoperate the interaction does not reduce the time of the clinical professionals, moving away from a real benefit for the healthcare institutions.

1.2 Foundations

There are multiple choices for both the application domain and target individuals in robotics assistance. Achieving a complete generalization is sometimes impossible and to establish a focus and specialization is essential. For this reason, although most of the fundamentals of this thesis can be applied to other areas or other types of patients (dementia in elderly, healthy habits education or post-stroke recovery in adults), this work has focused on the processes of neurorehabilitation and development in pediatrics.

Prior to the description of objectives, it is important to familiarize the reader with the fundamentals on which this work is based. This thesis presents an interdisciplinary approach in which four areas of knowledge are integrated to **define and evaluate child-robot interaction models and frameworks, as well as other methodological elements associated with the effective development of autonomous socially assistive robots in pediatrics**. Figure 1.1 shows four circular segments containing the foundations that support the proposal of this thesis: neurorehabilitation, gamification, socially assistive robotics and artificial intelligence. The inclusion of these areas tries to respond to the different identified problems.

- **First foundation**: neurorehabilitation interventions typically focus on plasticity by repeating certain exercises [Dobkin 2004]. Neuroplasticity allows the nervous system to recover from injuries or disorders [Byl et al. 2003]. An intense and continuous training favors the establishment of new connections to recover the functionality of the affected part [Leocani et al. 2006].
  Identified problem: "these routine and repetitive exercises tend to cause demotivation and loss of interest [Calderita et al. 2014a]".

- **Second foundation**: including gaming mechanisms in therapy moves towards a playful perception of the intervention. Gamification is based on positive reinforce-

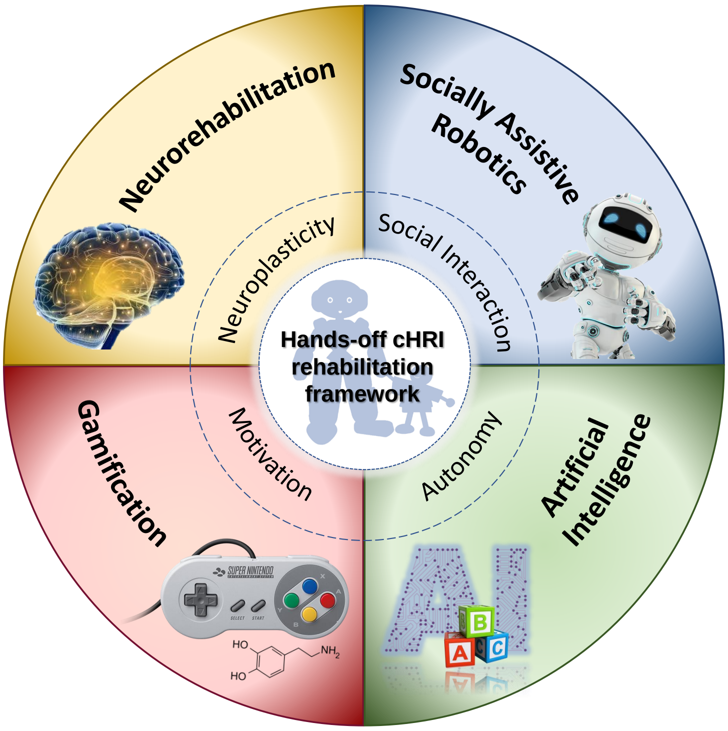

Figure 1.1: Foundations of the thesis.

ment and immersion of the patient to improve their motivation and commitment to the treatment [Deterding et al. 2011].
Identified problem: "In some cases, a gamified therapy may not solve the communication and/or trust problems between the patient and the therapist [Kanner et al. 1943, Dawe et al. 2019]".

- **Third foundation**: a socially assistive robot can be a communication interface with enough credibility for the patient. A robot-assisted therapy can stimulate better responses and a proactive behavior from pediatric patients [Feil-Seifer et al. 2009, Lee et al. 2012].
Identified problem: "most robotic approaches lack complete autonomy or propose solutions based on teleoperated interaction without any release of workload from clinical professionals [Belpaeme et al. 2013a]".

- **Forth foundation**: artificial intelligence techniques based on automated planning and machine learning are promising for the autonomous control of the interaction. Cognitive architectures based on this paradigm have proven to be adequate in the search for actions in robotic real environments [Romero-Garcés et al. 2015, Bandera et al. 2016].

1.3 Objectives

Based on these four foundations, this thesis aims to **define and evaluate child-robot interaction models and frameworks, as well as other methodological elements for non-contact robotic rehabilitation to augment pediatric interventions**. The designed framework must be provided with an intelligent system that controls a social robot so that it interacts autonomously with a pediatric patient in therapeutic sessions. These sessions should be composed of playful immersive activities, and based on reward and positive reinforcement. The clinical professional should be able to easily deploy and configure the system, as well as to obtain reports from patients after each session. The robotic interaction framework is proposed as a complementary tool to traditional rehabilitation sessions, so its use is limited to health professionals.

For this purpose, and as it is a very recent line of research, a user-centered approach is proposed by involving the user during each phase of the design and development of the system [Ting et al. 2017]. This means that the development of the prototype will not start with all the knowledge a priori, but the system will undergo improvements progressively after each evaluation, in which the deficiencies will be detected and solved.

According to what has already been discussed, the following objectives are defined:

1. Analyze the state of the art of the four fundamental areas and identify which aspects are integrable in the neurorehabilitation domain. The effort in knowledge engineering will help cover the gaps in such a recent line of research. For this, independent studies must be done of:
    - The procedures of therapies based on neurorehabilitation focusing on a patient profile.
    - How social robotic platforms can improve therapeutic interventions.
    - Different gamification mechanisms applied to therapy.
    - The autonomy of the system regarding to control the interaction through automatic decision making and adaptation of the system through learning techniques or expert knowledge.
2. The next objective focuses on the framework design and the initial prototype development. This phase receives clinical support from the area of psychology, physiotherapy and occupational therapy.

- Design a child-robot interaction framework for non-contact rehabilitation that integrates all the aspects analyzed in the previous objective.
- Development of a functional prototype intended to cover certain needs that are of interest to health professionals.

3. Since not all the knowledge is available a priori, the evaluation phase is integrated with the improvement of the system. A user-centered prototyping will be applied, so improvements will be incorporated responding to the user's needs that arise in each of the evaluations. Therefore, this goal is focused on defining different evaluation scenarios to expose the platform to situations close to the real practice: a first contact to get closer to the target individual, a long-term experience to determine adaptation and personalization needs and an intensive intervention to evaluate the motivation and adherence to treatment.

4. The ultimate goal of this thesis is to demonstrate the feasibility of this child-robot interaction framework in real healthcare settings. In practice, the objective is to prove that the system is consistent with the four areas of knowledge:

    - The system conforms to the clinical guidelines, complies with the mandated objectives and is useful for health professionals.
    - The interaction provided by the social robot guarantees an active engagement improving the patient's experience during the interventions.
    - Integrating mechanisms of gamification in therapy improves motivation and, therefore, adherence to treatments.
    - The autonomy provided is so robust that no engineer is required either to control the interaction or to adapt the system.

5. During the evaluation process, capturing the impressions that the main stakeholders have about the platform is also fundamental. Although these evaluations may yield subjective data, this is a way that favors the improvement of the system and its future deployment. Tests and structured interviews help to respond to other evaluation factors of great importance such as the usability of the tool, the user experience, if the tool is accepted in society and the impact that the system has on society.

1.4 Outline

This manuscript is organized as follows: Chapter 2 presents the state of the art of the four main areas (neurorehabilitation, socially assistive robotics, gamification and robotic autonomy) by connecting the argument line of the thesis. Then, Chapter 3 explains the design process of the child-robot interaction framework. After that, Chapter 4 presents NAOTherapist, a prototype for physical rehabilitation, which is subsequently evaluated in Chapter 5. Next, Chapter 6 presents another case of use centered on infant motion encouragement based on the same paradigm. The document ends with Chapter 7 that raises the conclusions, future projections and contributions.

Chapter 2

Background and Related Work

Interdisciplinarity is a highly present term in this thesis, which occurs when different areas of knowledge relate to each other with defined relationships, so that their activities do not occur in an isolated, dispersed and fractionated way [Klein 1990]. In other words, all areas complement each other. The acquisition of different information sources is a necessary action for the researcher to get sufficient grounds for a consolidated research.

The foundations of this thesis arise from four different disciplines which, in most cases, are still in their infancy. These bases deal with very recent concepts in our history and present an unexplored field of new possibilities. While stating the ultimate goal of this work, four key points can be distinguished. The aim is to design a framework to: 1) enhance pediatric neurorehabilitation interventions 2) by maintaining a prolonged motivation of patients, 3) in which a socially assistive robot 4) makes its own decisions. These key points are directly related to the four areas of knowledge that are discussed in this chapter.

The concepts of neurorehabilitation in Section 2.1 provide a sufficient clinical basis for its application in physical therapy with pediatric patients. In order for these patients to maintain long-term motivation and engagement, Section 2.2 describes the foundations and related work in Gamification and Serious Games, as well as its application in physical and cognitive therapy. Afterwards, Section 2.3 continues with the definition of Socially Assistive Robotics and its application in non-contact rehabilitation. Finally, Section 2.4 discusses several alternatives of robotic control in relation to the autonomy of the robot in making decisions.

2.1 Neurorehabilitation for Pediatric Patients

In 1959, Ramón y Cajal postulated that the brain is in constant restructuring in response to the changing environment, which offers the opportunity to acquire and eliminate information throughout its life [Ramón y Cajal 1959]. This process was first defined as neuroplasticity by the neuroscientist Jerzy Jonorski [Konorski 1948] from the studies of William James [James 1890]. Neuroplasticity refers to the ability of the neurological tissue to reorganize, assimilate and modify the biological, biochemical and physiological mechanisms involved in intercellular communication to adapt to the stimuli received [Li et al. 2014]. Figure 2.1 shows an artistic representation of the concept of neuronal plasticity. From left to right, it reproduces the evolution of the neuronal tissue after the effects of learning.

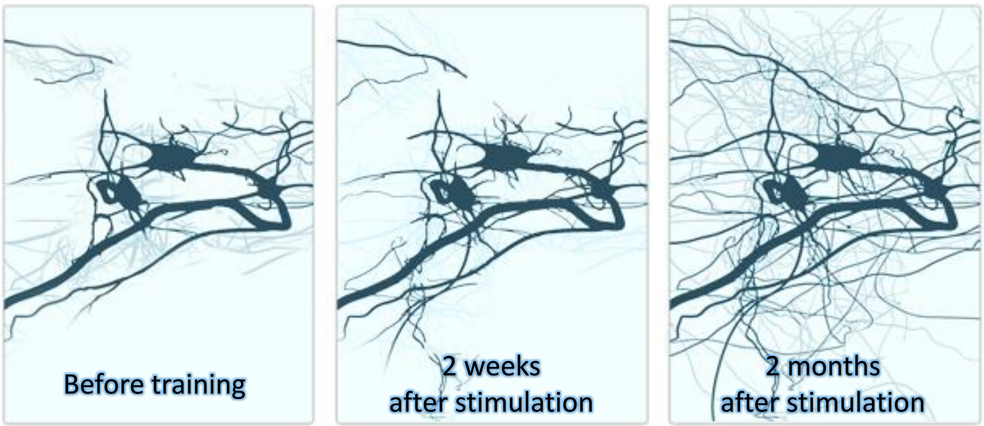

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Figure 2.1: Artistic representation of the concept of neuroplasticity.

When learning new tasks, new synaptic pathways are created and they are reinforced as the task is long repeated [Kandel et al. 2000]. Over time, this activity becomes something habitual that is done more naturally and effectively. In the same way, after a long time without performing a task, despite of having it learned in advance, these paths are dissipated and a relearning is required. This behavior shows that the brain of the human being is a living organ that needs permanent training and refreshing, and that is adapted and restructured with every received stimulation.

Some contemporary studies aim to demonstrate if these changes are made selectively in areas of the brain associated with certain activities, such as music training [Draganski et al. 2004]. For example, in one these experiments, a group of individuals learned to juggle for 3 months [Schlaug et al. 2009]. After this time, the authors used magnetic resonance imaging of the entire brain to visualize the learning-induced plasticity in the brains of the volunteers. It was determined that these individuals showed a transient and selective structural change in areas of the brain that are more associated with the processing and storage of complex visual movements related to the activity they had learned.

The ability to relearn is the main foundation of neurorehabilitation, which is a complex clinical process aimed at restoring, minimizing and compensating for the functional disorders that appear in individuals affected by a disability as a result of an injury to the nervous system [Krucoff et al. 2016]. This is a relatively recent concept that was first addressed after the Second World War, due to the countless injuries that survived with spinal cord damage and brain damage. There was a need to establish new guidelines and recovery procedures so that these survivors could regain some independence in their daily lives [McDowell 1994]. Among the most commonly intervened conditions are: stroke, acquired brain injury, Parkinson's disease, multiple sclerosis, cerebral palsy, etc.

In order to help patients whose neuromuscular system has some type of deficit, neurorehabilitation treatments typically focus on plasticity (induced neuroplasticity) by repeating certain exercises [Dobkin 2004]. Neuroplasticity is a potential for adaptation that allows the nervous system to recover from injuries or disorders [Byl et al. 2003]. An intense and continuous training by exercise repetition favors the establishment of new connections to recover the functionality of the affected part [Leocani et al. 2006]. In this context, neurorehabilitation aims to positively influence the skills and attitudes of the person with disability and their affective environment: in skills, to achieve in each case the highest degree of personal autonomy possible, and in attitudes, to restore self-esteem and a constructive emotional disposition able to adapt to the new situation and enhance personal resources, to achieve social reintegration active and satisfactory.

During the recovery process, specialists treat all aspects related to the patient's well-being. Neurorehabilitation covers a wide spectrum of issues in the life of the individual, from the psychological to occupational, teaching, mobility independence, communication, nutrition and other daily aspects [Kitago et al. 2013]. For this, the healthcare facilities require specialized professionals in each of the areas to be treated, typically: physiotherapy, occupational therapy, psychological therapy, speech, vision therapy, and language therapy. All these therapies seek to improve the functional capacity of the patient, their autonomy and encourage their reintegration in society.

The field of neurorehabilitation is relatively recent and although many interdisciplinary works present innovative and technologically advanced treatments, their usefulness is still questioned. The general reason is the lack of a research experience long enough in time to demonstrate that these approaches contribute to improve the patients' quality of life.

2.1.1 Early Diagnosis and Intervention

Growth and child development are two closely linked phenomena that vary in each individual. During the first 6 years great physical, intellectual, social and emotional changes take place in a very short period of time [Bijou 1976]. In fact, during the first 6 months of life is when the infant experiences more changes in the psychomotor aspect, and between 6 and 12 months reaches a certain degree of independence that opens a stage of discovery and curiosity. Infants engage in exploratory movements that allow them to learn the connection between their body and the physical world. Additionally, the spontaneous movements infant produce modulate into task-specific actions such as reaching, crawling, and walking [Gibson et al. 2000, Thelen et al. 1994]. Between 12 and 24 months begins to take its first steps, and from 2 years and up, social and cognitive development take the lead of the stage of growing. In summary, the development during the first two years focuses on motion control and displacement. Once this autonomy is acquired, the infant matures cognitively and socially. This chronology of development explains the importance of a thorough monitoring of the child's growth to establish a typical development from the physical [Noritz et al. 2013] and cognitive [Zwaigenbaum et al. 2015] point of view.

The main characteristic of this population is its enormous heterogeneity, since in such early stages, the aspects in the development and behavior patterns can vary enormously between individuals. That is why it is difficult to establish general guidelines and professionals need to make a more personalized analysis. Children who display early motor delays often can have the initial signs of later developmental impairments [Ghassabian et al. 2016]. In fact, motor, cognitive and social development in infancy are interactive domains, so if an infant has a deficit in one domain this deficit can affect all three domains, thus it is important to provide early interventions for infants to ensure the development of all three domains [Lobo et al. 2013].

The American Academy of Pediatrics recommends professionals monitor the child development at all preventive care visits and the standardized evaluation of the development of all children at the ages of 9, 18 and 30 months [Noritz et al. 2013]. Approximately 9% of all infants in the United States are at risk of development and could potentially benefit from early intervention services to address motor, cognitive, and/or social development [Rosenberg et al. 2013]. All development domains, such as motor, cognitive and social are related, thus an intervention in one domain may provide benefits in all areas of development [Lobo et al. 2013]. Despite this, the current standard of care for early intervention practice is to provide infrequent, low-intensity movement therapy or no intervention in infancy [Roberts et al. 2008, Tang et al. 2012]. New research has shown that early, intense, and targeted therapy intervention has the potential to improve neurodevelopmental structure and function [Holt et al. 2011]. Despite this potential gain, it can be challenging to find feasible and resource-efficient ways to deliver this type of intervention in infancy.

For children with deficits, or at risk of suffering from them, early stimulation is a fundamental part in the development of the first three years of life, since it allows to enhance physical, cognitive and sensory abilities depending on the affected areas [Majnemer 1998]. In pediatric rehabilitation, one of the main objectives of the early motor stimulation is to optimize the patient's potential by exploiting the concept of neuroplasticity, and compensate for their deficits so that they can improve their quality of life and have a full and satisfying life in the future. To this end, neurorehabilitation therapy requires a constant commitment of the patient and their relatives, and adherence to an intensive treatment prolonged over time. To be effective, the patients should start their therapy as soon as possible, but following a personalized treatment that is adapted to their condition and progression [Mahoney et al. 2004]. Both issues are not always easy to satisfy, given the limited availability of professionals and the lack of time to monitor the progression. Researchers also propose that neurological deficits could be identified by collecting high quality spontaneous movement patterns from wearable sensors and kinematic analysis systems [Groen et al. 2005, Hadders-Algra et al. 1999, Prechtl 1997].

2.1.2 Infant Brain Damage

Infant Brain Damage is a serious condition that happens after some complication during delivery or pregnancy of the baby [Levine et al. 1984]. Although medicine has evolved in favor of obstetric instrumentation and methodology, there are still cases that affect millions of babies every year. There is a variety of possible causes and the baby can mostly experience long-term permanent neurological deficits and a wide range of physical problems. In order to improve the quality of life of the affected patient, it is of vital importance to establish an early diagnosis to know the causes, as well as to administer the best treatment methods. Among the most common causes that explain the brain damage in childbirth are: oxygen deprivation, physical trauma in the delivery or infections of the mother's body. All of them may lead to serious consequences that produce disabilities or psychological problems [Nelson et al. 1984]. Although multiple conditions may occur as a result of these complications, this thesis aims at focusing on two of best known and usual: Cerebral Palsy and Obstetric Brachial Plexus Palsy.

The human being is the only existing mammal that usually walks on two legs and whose brain is the largest and most complex in relation to his body. Until adulthood, this organ expands by a factor of 3.3 compared to 2.5 in chimpanzees [DeSilva et al. 2006]. This evolution has great implications at birth. The anatomy of women has also evolved: the morphology of the pelvis and the birth canal narrowed and twisted. This situation, added to the increase of fetus' head and shoulders width, means that the birth process of modern humans has very little margin for error [Sreekanth et al. 2015, de León et al. 2008]. This situation has required a greater specialization of obstetric techniques to reduce the likelihood of complications such as shoulder dystocia, which occurs when the head of a baby passes through the vagina during birth, but its shoulders get stuck inside of the mother, as is shown in Figure 2.2. Hyperextension of the head can exert an attraction on the nerve collection. Due to malpractice in this situation, the baby may suffer damage to the brachial plexus leaving a long-term sequel.

Obstetric Brachial Plexus Palsy (OBPP) is a loss of movement or weakness of the affected upper-limb produced when the collection of nerves around the shoulder are damaged during the birth. This group of nerves is called brachial plexus [Ouzounian 2014]. This kind of complication has been reduced due to the improvements of the birth process and only 1.5 of every 1000 live births present this injury. The prognosis of this injury will be marked by the number of nerve roots that have been affected, the severity of the trauma that caused it and the remaining functional capacity [Chauhan et al. 2014]. Other common causes of Brachial Plexus Palsy are produced by vehicle accidents or infections. For all of these cases, physical therapy is recommended to recover the total or partial range of arm movements [Crofts et al. 2016].

The most common effects of OBPP can be classified as:

- Motor: the brachial nerve section produces motor paralysis with a loss of reflexes of the tone with the consequent muscle atrophy and flaccidity.

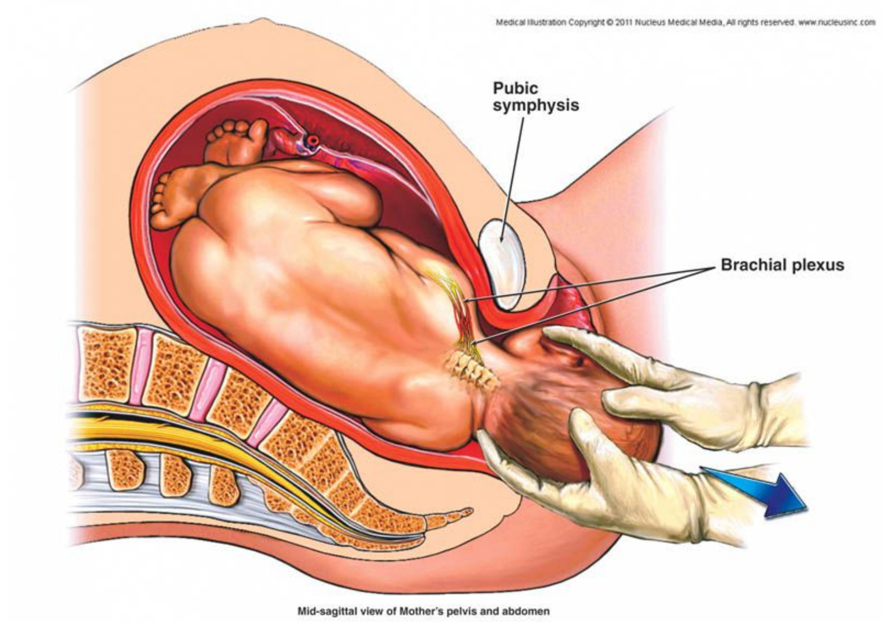

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Figure 2.2: Bachial Plexus Injury.

- Sensory: the patient may lose cutaneous and proprioceptive sensations.
- Autonomic: if the injury affects the sympathetic nerves, there is a loss in sweating and temperature control, since the affected extremity adopts the ambient temperature.

Another condition is **Cerebral Palsy** (CP), which is the term that includes the non progressive conditions related mainly with the impossibility to have full control of the motor functions [Bax et al. 2005, Krägeloh-Mann et al. 2009]. This condition is typically caused by complications during the pregnancy or birth trauma, and also due to an infection or an accident. CP is caused by a specific injury, which occurs only once, and whose effects are prolonged or even lifelong. Birth asphyxia is a very common cause: a few minutes of oxygen deprivation can lead to irreversible brain disorders such as cerebral palsy, autism, attention deficit hyperactivity, impaired vision.

Although the produced injury is punctual, the clinical manifestations are affected and musculoskeletal problems get worse if they are not treated continuously [Krigger 2006]. In general, the treatment is aimed at improving mobility and postural control of the patient to improve their autonomy. In relation to the patient's muscle tone, the most common type of CP is spastic, in which patients have excessive rigidity in their movements with a weak musculature, as well as problems in walking and handling tasks.

Depending on the spread of the lesion, the CP is classified as follows:

- Monoparesis: affects a limb (usually upper limb)
- Diparesis: affects both lower limbs
- Hemiparesis: affects one side of the body, upper and lower limb.
- Tetraparesis: affects all four limbs.

Sixty percent of children with physical impairments are classified under the cerebral palsy umbrella term. For each 1000 births there are two or three cases which present this symptomatology and it is estimated that 650.000 European families have a child or adult with cerebral palsy [Castelli 2011]. This condition limits the autonomy of the patient in common tasks like dressing up themselves, eating or communicating [Hensey 2009]. There is not any cure and patients have to live all their life with this incapacity. The affected abilities must be improved through rehabilitation therapy. A well developed treatment can raise the ability to walk, reduce muscle rigidity and even prevent future malformations [Krigger 2006].

The principles of neuroplasticity are the fundamental part for the recovery of these patients who are in a maturing stage [Mundkur 2005]. Their nervous system is still growing and in constant change, so therapies based on exercise-induced neuroplasticity take advantage of this high reorganizing capacity [El-Sayes et al. 2018]. There are documented evidences that state a functional recovery of poststroke patients from 6 months to 7 years old through neuroplasticity-based rehabilitation [Byl et al. 2003]. Functional recovery in patients with cerebral palsy has also been documented in intensive rehabilitation therapies in which they are induced to practice the affected limb [Gordon et al. 2007].

2.1.3 Clinical Rehabilitation Protocol

In the intervention of the patients with the pathologies described in Section 2.1.2, different lines of action can be applied. After suffering a traumatic injury, health professionals make an early diagnosis to determine the appropriate treatment that the patient should receive. Although in some cases these patients may need a very specific surgical intervention, this section focuses on the explanation of the rehabilitation protocol that these patients should follow during a long term. The presented clinical guideline belongs to the child rehabilitation unit of the Virgen del Rocío University

Hospital (VRUH) in Seville. This hospital is the main health institution which has provided clinical support during the development of this thesis. At the same time, this section raises the problems that health institutions encounter when administering these treatments, and which at the same time establishes the bases and nourishes the motivation of this work.

As explained above, rehabilitation should begin early, since the final result and the degree of functional and neurological recovery will depend on it. In the same way, parents and caregivers should be familiar with all the treatment and be committed throughout its duration, since in many cases, it is recommended to continue with the exercises at home. The main objective is to guarantee the necessary conditions for the functional recovery of the patient thanks to the acquired nerve regeneration. For this, a strong commitment and a constant regularity are necessary.

The process of rehabilitation of patients with OBPP and CP has a multidisciplinary approach within the clinical setting, in which different professionals intervene: physiatrists, physiotherapists, occupational therapists, psychologists, etc. It is important to understand the traditional rehabilitation procedure upon which the design objectives of this work are formulated. Figure 2.3 shows this procedure defined in the clinical protocol of the VRUH. Each step comprises a set of guidelines that have been considered during the development of this proposal. This process involves three actors:

- The physician or physiatrist is the specialist in rehabilitation who makes the diagnosis of the patient, establishes the clinical objectives and carries out subsequent evaluations to update the therapeutic parameters if required.

- The therapist designs, guides and supervises the therapy sessions with the patient. He is in charge of guaranteeing that patients achieve their goals by encouraging them during the training.

- The patient is the primary user and beneficiary of the therapy. In this context, the patients are children with upper-limb motor disorders who have to have weekly rehabilitation sessions.

As shown in Figure 2.3, the therapeutic procedure starts with a primary evaluation of the patient according to his medical record. The results of the diagnosis together with the expectations of the patient are the elements for determining the therapeutic objectives and particular constraints of the sessions. For instance, if the patient hopes to dress or eat by himself, the physician can establish a therapy configuration suitable

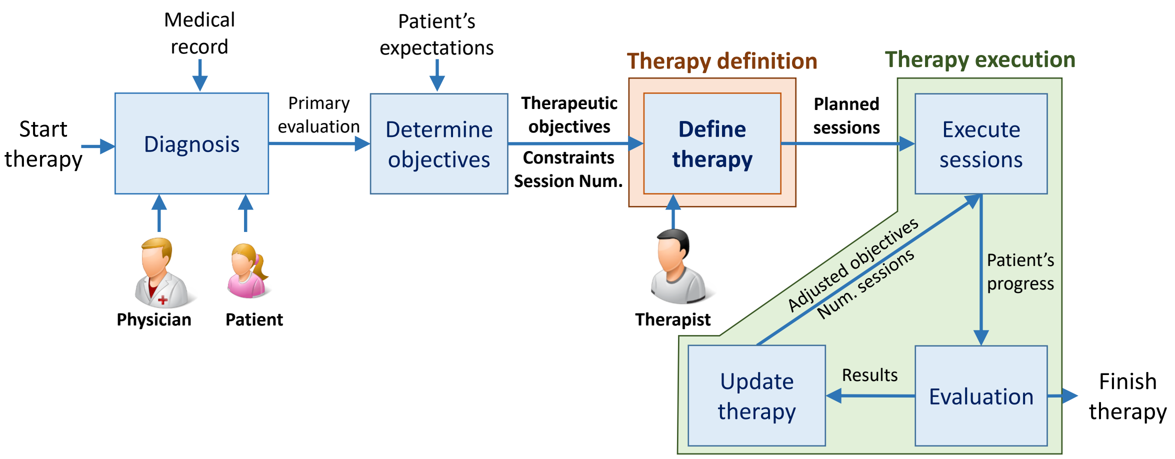

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Figure 2.3: Rehabilitation Procedure.

for the motor skills which allow the patient to achieve this goal. The progress of patients according to their expectations and desires is measured using Goal Attainment Scaling (GAS) [Turner-Stokes 2009a]. This evaluation tool helps physicians to obtain a numeric estimation of the accomplishments of the patients to their specific goals. The rehabilitation procedure comprises two major steps: therapy definition and execution in Figure 2.3.

In therapy definition step, the therapeutic objectives, constraints and number of sessions are used as the input to design a full therapy plan. Planning sessions require a suitable configuration of exercises to be established that fulfills the clinical criteria. This planning step is a cumbersome task for therapists in terms of time and effort. Moreover, the design of the training plan depends greatly on each therapist and their experience. A lack of planning for the sessions may threaten the quality of the treatment and could mean that not all of the clinical aspects are covered.

Therapy execution is the training step, in which all of the planned sessions are executed. Exercises consist of repetitive movements to strengthen the affected joints. These traditional methods may cause boredom and laziness. Therapists have to deal with this situation by investing much time and dedication getting an active engagement and commitment of the patient. Despite this effort, the treatment development may be tedious, so the effectiveness of the therapy is affected [Calderita et al. 2014b]. This situation can delay the recovery of the patient increasing treatment costs.

The patients of this work are children, therefore they require much more attention to avoid distractions and get the most out of time the care have for each session.

Therapies are very long and consist in continuous repetitive movements to train the affected limbs. These routine exercises tend to cause loss of interest in the patients. To solve this problem much dedication by qualified personal is needed [Calderita et al. 2014a]. Despite this effort, the objectives of the therapy may not be achieved. The loss of motivation and engagement to continue with the treatment can obstruct dramatically the recovery and affect the quality of life not only for the patient but also for his/her family. This is also harmful from the economic and professional point of view due to the high effort/cost that it requires [Meyer-Heim et al. 2013].

2.1.4 Evaluation and Metrics

This section describes the assessing instruments for the evaluation process available to the clinical staff of VRUH. The diagnosis is made first before beginning the rehabilitation process as explained in Section 2.1.3. In the first instance, the physiatrist must perform a series of examinations to determine the degree of disability and mobility. Measuring scales are tools that help the physician to translate the patient's condition into numerical or discrete data that are relevant to the disease and allow the patient to be classified. Once the patient's condition is known, the therapeutic objectives are established. The metrics and scales listed in Table 2.1 are taken into account for measurement in patients with OBPP and CP, and that are of interest to this thesis.

Range of Motion (ROM) refers to a set of measures that allow to quantify the mobility of joints through goniometry and centimetric measurements [Reese et al. 2016]. An active and a passive measurement is made. When using a goniometer, the following should be taken into account:

- The body plane on which the movement is performing: sagittal, coronal and transverse planes.
- Take reference points and locate the extreme positions.
- Place the center of the goniometer on the axis of the joint.

For the transcription of results, the values are grouped in: Flexion (F) /Extension (E), Abduction (ABD) /Adduction (ADD), External Rotation (ER) /Internal Rotation (IR). The notation is the Neutral Zero International Method in which all angular movements are measured from zero position [Ryf et al. 1995]. Points of reference are sought and the two movements of the plane are measured. Each movement is collected between three values: two refer to the extremes and the zero. For example: FE 150/0/5, refers to a 150^o flexion that passes through zero and makes an extension of 5^o.

Assessment	Pathology	Instrument	Value	Dimension	Objective
Range of Motion (ROM)	OBPP, CP	Goniometer	Numeric	Objective	Evaluate the range of mobility of each of the joints
Medical Research Council Muscle (MRC)	OBPP, CP	Observation	Scale	Subjective	Evaluate muscle strength / balance
Manual Ability Classification System (MACS)	OBPP, CP	Observation	Scale	Subjective	Functionality of the upper limbs
MALLET Scale	OBPP	Observation	Scale	Objective	Detect functional changes of the shoulder and arm
Quality of Upper Extremity Skills Test (QUEST)	CP	Observation	Numeric	Objective	Evaluate movement pattern and quality manual function
Goal Attainment Scaling (GAS)	OBPP, CP	Interview	Numeric	Objective	Method to evaluate the patient's improvement with respect to established objectives
Nine Hole Peg Test (9HPT)	OBPP, CP	Board Game	Numeric	Objective	Degree of concordance and precision of movements

Table 2.1: Metrics & Instruments Overview.

Another example: FE 150/25/0, means that it makes a 150° flexion and 25° is missing to reach the zero position (it can not stretch the arm completely). The amplitude of the movement is the mobile angular sector between the two extreme positions. So for the first example, 150/0/5, its amplitude is calculated as $150 - 40 = 110$. The amplitude of the second example (150/25/0) is $150 + 10 = 160$.

Medical Research Council (MRC) allows healthcare professionals to measure muscle strength and balance [Paternostro-Sluga et al. 2008]. It is a reliable scale to evaluate the muscle weakness described in "Medical Research Council". It also helps when determining peripheral nerve damage.

At the time of the evaluation, the patient must be in a comfortable, relaxed and stable position that allows only the part under examination to work. Avoid those movements that come from other agonist muscles to the muscle that you want to assess. The strength of the patient is graded on a scale of 0 to 5. A functional evaluation is then performed based on a clinical graduation scale from 0 to 10.

Manual Ability Classification System (MACS) describes how children (ages 4 to 18) use their hands to manipulate objects in daily activities [Eliasson et al. 2006]. It is a functional description that complements the patient's diagnosis.

MACS describes five levels. The levels are based on the ability of the child to self-initiate the ability to manipulate objects and their need for assistance or adaptation to perform manual activities in everyday life: play, eat, dress, etc. The objects to be manipulated are according to the age of the patient.

MALLET Scale is a qualification system to document functional changes of the shoulder examining the global movement of the limb in children over 2 years of age with OBPP (requires patient cooperation) [Eng et al. 1996]. It graduates from I to V and includes active abduction, external rotation, hand-nape, hand-back and hand-mouth.

Quality of Upper Extremity Skills Test (QUEST) is designed to assess movement patterns and the quality of manual function in children with cerebral palsy between 18 months and 8 years with neuromotor dysfunction and spasticity . The manual function is evaluated through four domains that contain a total of 36 activities: 1) dissociated movements, 2) grip, 3) standing support, 4) postural reactions [DeMatteo et al. 1993].

Each activity will be assessed with a V sign if the patient is able to complete the activity (2 points). With an X if you can not complete the activity (1 point) and with an NT if it can not be assessed. The score will be added at the end of each section of the test. The patient will receive a percentage score for the four domains of the QUEST scale. The higher the percentage, the better the quality of movement. The final assessment can take negative values in the event that all the postures of the activities are atypical and the maximum score is 100.

Goal Attainment Scaling (GAS) is a method to evaluate the improvement and progress of the patient on a series of individual objectives established between the doctor and patient [Turner-Stokes 2009b]. These objectives establish a commitment with the patient. In practice, each patient will have their own objectives and a normalized score according to the assessment made on each of these objectives. In this way, the scale allows a statistical analysis of the results of the patients.

Nine Hole Peg Test (9HPT) is an instrument used to measure the degree of concordance and precision of movements [Mathiowetz et al. 1985]. To do this, a board with 9 holes 1.3 cm deep and separated by 3.2 cm is used. It comes with 9 cylinders that fit into each of the holes. To calculate the time a chronometer is also necessary. The objective is to introduce all the cylinders, one by one in the holes in the shortest possible time.

First, the dominant hand of the patient must be identified. If necessary, you can let do a couple of rounds of testing with each hand. When the test is started, the patient should start a first phase with his dominant hand and the time will start to run when he touches the first cylinder and will end when he releases the last one already placed. When the patient has finished, a second phase will start where he will repeat the test with the other hand. At the end of the test, the specialist should collect the results with the date and time it has taken to perform each phase.

2.1.5 Discussion

This section has offered an overview of the neurorehabilitation process in pediatrics. Neuroplasticity has been introduced as a key concept in neuroregenerative therapies, which also requires a diagnosis and early intervention to achieve better results [Li et al. 2014]. This reorganizing capacity of human beings facilitates relearning and sustains the bases of physical and cognitive therapies.

Both Cerebral Palsy and Brachial Obstetric Paralysis are the two conditions described and whose patients are the main beneficiaries of these therapies [Bax et al. 2005, Ouzounian 2014]. These movement disorders may threaten the quality of life and well-being of patients for in their daily life tasks [Dickinson et al. 2007]. The majority of these patients have to live with disabilities throughout their life, and it is necessary to understand how these conditions affect each patient in order to design a personalized treatment [Ramos et al. 2000, Krigger 2006]. The rehabilitation program is an essential part of spasticity management [Shamsoddini et al. 2014]. The treatment is very hard and tiring, so incorporating new ways of rehabilitation for children may improve their motivation and commitment to the therapy, such as playful activities.

2.2 Gamification and Serious Games

Beyond entertainment, computer games can have other more serious purposes, among which are: improving healthy habits, education, physical or cognitive therapy, etc. Serious games and gamification are concepts that contribute to these purposes, but with different perspectives [Fleming et al. 2017]. Serious games refers to those games with serious purposes and at the same time they represent an enjoyable experience for the user [Fleming et al. 2014]. In contrast, gamification relates to the implementation of game mechanisms in non-game contexts [Deterding et al. 2011]. A gamified intervention would not be a completely gaming experience, but it contains certain elements such as punctuation, rewards and levels, to improve motivation, concentration and productivity. By introducing game mechanics it is possible to promote the active participation of individuals in the activity, moving towards a playful perception, positive reinforcement and a rewarding and immersive experience [Deterding et al. 2011]. Immersion is a fundamental aspect of gamification with which an improvement of the patient's concentration is guaranteed. An immersive game manages to make the patient believe that the task is so real that the evoked emotions are very similar to those in real life. The effort-reward effect, so present in games, influences the release of dopamine. This chemical release has proven to favor concentration and learning [Bao et al. 2001].

Although the scope of gamification and serious games is very broad, this section focuses on its application to health. Specifically, Section 2.2.1 describes the application of serious games to mental health, as well as its benefits and implications from the psychological and behavioral point of view. After this, Section 2.2.2 offers an overview of gamification applied to physical therapy, an attempt to strengthen rehabilitation.

2.2.1 Serious Games in Mental Health

Approaches based on serious games have begun to extend the area of mental health. Although there is still much work to be done, different authors study the potential benefits of these games from the psychological aspect, education and behavioral changes [Fleming et al. 2017]. Among the main advantages of including game-based approaches in therapies are: A) "appealing potential" thanks to the current popularity of video games that covers a greater number of beneficiaries [Mojtabai et al. 2011], B) "engaging potential" due to its attractiveness and playful character [Fleming et al. 2016], C) "effective potential" since it influences the behavior of the user and can achieve the proposed objectives [Cheek et al. 2015].

Engagement is a fundamental aspect that can be exploited in different ways. Hamari and Tuunanen along with other contributions identified six key motivational orientations that support this engagement in games [Hamari et al. 2014b]. These six characteristics are: achievement, sociability, domination, exploration, immersion and motivational escape. The main motivation of the user to engage in a game is defined by these categories. The game designer will include one or the other depending on the type of game, context, demographic group, clinical interest or patient preferences.

The virtual and augmented reality have occupied an important position in the development of games for therapeutic purposes [Gutiérrez-Maldonado et al. 2016, Laforest et al. 2016]. These technologies offer an interactive immersion in a virtual or augmented environment through sensory stimulation increasing user engagement. Some of these games are designed for therapeutic purposes, but there are few studies still not significant enough to demonstrate the benefits in the therapeutic field. However, all authors agree that both technologies are very promising with a long research ahead [Fleming et al. 2017].

2.2.2 Gamification in Physical Therapy

Gamification is a learning technique that translates the gaming recreational principles to other professional fields such as education, therapy or psychology, aiming to achieve better results when, for example, better learn some knowledge, modify a behavior routine, make the therapy enjoyable or reward any particular action [Deterding et al. 2011]. Gamification has gained much ground as a learning or working methodology due to its playful nature. It is based on encouraging motivation through the game mechanics and promoting the spirit of achievement. This facilitates the acquisition of new skills in a more fun and committed way, generating a positive experience. It has been shown that the effects of gamification are very dependent on the area of application and users [Hamari et al. 2014a]. Works with children are very relevant, in which the gamification methodology is applied to increase the users' motivation while completing the laboratory studies [Brewer et al. 2013].

Game designers generally lack clinical or therapeutic knowledge. Commercial video games can barely be used as a therapeutic instrument, since they are not clinically validated or adapted to the patients' pathologies. In order to create gamified sessions for therapeutic purposes, mixed teams (clinicians and designers) must be formed to develop patient-centered games with a high level of customization. Three main uses of games in pediatric physical therapy are distinguished in the literature [Janssen et al. 2017]:

1. The principles and game mechanics allow the creation of playful environments in therapeutic sessions. This would increase the performance, concentration and motivation of the patients. Therapists will be responsible for gamifying the sessions by developing the game mechanics and guiding the patient throughout the process.

2. Commercial games are another entertainment strategy in the execution of the treatment. While patients are playing a game, they may be walking in a treadmill, using a bicycle, standing on a balance bench or training with ballasts.

3. Applied games or adjustable exergames. With the help of the therapist, the decision is made about which games fit better with the patient's therapy. They do not have to be intended for therapeutic purposes, however they can be used as such if the clinical professional considers them appropriate. In this regard, there are also popular platforms such as the Wii console that have been used in studies to improve the balance of patients with cerebral palsy [Tarakci et al. 2013].

Gamification is a very promising area applicable to almost any field where you want to improve the performance and motivation of participants. However, although most of game mechanics are already known, there is still a knowledge gap on how to apply these techniques in real healthcare environments [Janssen et al. 2017]. It is important to design general methodologies, models and/or toolkits that can be applied to different pathologies, use cases, needs and environments. In this sense, pediatric health professionals can be provided with sufficient strategies and tools to improve adherence to treatments.

2.2.3 Discussion

As previously mentioned, gamification is defined as the inclusion of game mechanics in non-game environments, as in physical or cognitive therapy [Janssen et al. 2017]. Serious games refers to games with serious purposes [Fleming et al. 2014]. In both cases the main objective is to get the patient involved in a playful experience throughout the treatment, instead of the obligation to go to the hospital. For this, immersion in the game together with the gaming perceived reward are the main ingredients to get engaged and committed in a gamified therapy. Moreover, the received rewards evoke the release of dopamine, a substance that promotes concentration and learning [Bao et al. 2001, Seitz et al. 2009]. Therefore, both playful contexts seem to gather the necessary components to improve adherence to rehabilitation programs.

However, the incorporation of gaming mechanisms to therapy may not solve all the problems that may arise. Sometimes therapists are not able to perform certain therapies satisfactorily, due to the difficulty in connecting and communicating with the patient. A clear example happens in some cases of patients with cognitive disorders, who are not able to look in the face of their therapists and with whom it is very complicated to establish enough complicity to perform any activity [Kanner et al. 1943]. In this line, numerous works have demonstrated the effectiveness of using a social robotic platform that breaks these barriers [Dawe et al. 2019]. These works state that a robot-assisted therapy can stimulate better responses from pediatric patients [Lee et al. 2012, Miyamoto et al. 2005]. The main advantage for the therapist is the use of the social robot as a communication interface with the patient to work on the treatment.

2.3 Socially Assistive Robotics

Socially Assistive Robotics (SAR) is a growing field whose purpose is to use robots to undertake certain social needs. This term represents all those robotic platforms that provide a service or assistance to people through social interaction [Feil-Seifer et al. 2005a]. SAR is a recent line of research that is still in its infancy and that opens a wide range of applications. In the last ten years, a wide variety of assistive devices have been developed as support systems and many of them have gained far-reaching acceptance among users and professionals alike [McMurrough et al. 2012]. This has opened up new lines of research in different application domains, including physical [Maciejasz et al. 2014] and cognitive rehabilitation [Tapus et al. 2009].

This work contributes to the field of SAR-based neurorehabilitation treatments in pediatrics. Rehabilitation robotics seeks to introduce new and reliable technologies into the therapeutic process [Huang et al. 2009]. As with other fields of application, robotics offers interesting advantages, such as the possibility of performing automated and personalized treatments that reduce the fatigue associated with repetitive and monotonous exercises [Gilliaux et al. 2015] or its ability to integrate sensors that provide a quantitative estimation of initial conditions and recovery. SAR approaches in pediatrics are also highlighted by their great motivational potential and by their ability to interact with patients who suffer problems of socialization or communication [Dawe et al. 2019]. These new robotic therapies open a new perspective for health professionals as tools that help to stimulate better responses from patients.

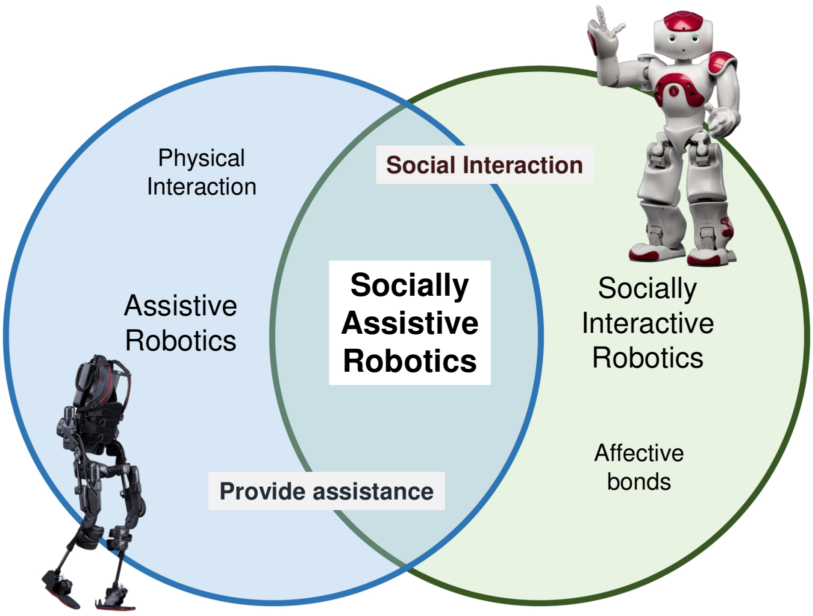
2.3.1 Definition of Socially Assistive Robotics

Most of the work developed in the area of robotic rehabilitation has historically been based on physical contact [Maciejasz et al. 2014]. In some cases, they have been referred to as *hands-on* or *wearable robotic technology*. These techniques have transformed the practice of rehabilitation into a guided process of passive rehabilitation [Burgar et al. 2000]. This means that the patient is helped by a robot to appropriately exercise the affected extremity. This hands-on interaction between the patient and the robot involves complex restrictions related to patient safety, which makes this area of research very promising in the seek for a solution [Hesse et al. 2003]. Additionally, compliance with these requirements increases costs for both the patient and the health-care provider, which is not always affordable.

In general, systems based on physical contact are called assistive robotics; however, they do not always encourage active participation from the patient, and they are difficult to adapt to occupational therapy, where rehabilitation is oriented toward functional activities [Cuadrado 2009]. For instance, *wearable* robots or exoskeletons for patients with spinal cord injuries increase the range of movements, thus improving their motor skills [Perry et al. 2007]. Advanced mobility aides are also developed for elderly and visually impaired people as well [Ni et al. 2015, Dubowsky et al. 2000, Lacey et al. 1998]. There are also robotic platforms that aim to rehabilitate an affected limb by carrying out movements with a controlled resistance [Burgar et al. 2000, Kahn et al. 2001] and others combine virtual games with remote control techniques for the same purpose [Song et al. 2016]. Robot-Mediated Therapy (RMT) devices are available for children. This technology "wears" the patient's body driving their joints during the rehabilitation process [Castelli 2011, Garcia et al. 2011, Meyer-Heim et al. 2013].

Clinical experimentation demonstrates that a patient's motivation is key to successful implementation of neural rehabilitation therapies [Colombo et al. 2007] and relates directly to patient's engagement to the treatment. Another line of research attempts to integrate the motivation factor, including the "social" aspect, into robotic-based rehabilitation therapies. The new robots aim to provide service and assistance to users through social interaction. As shown in Figure 2.4, this new area has emerged from the intersection of assistive robotics and social interactive robotics [Fong et al. 2003], giving rise to SAR [Feil-Seifer et al. 2005b]. SAR establishes a connection between rehabilitation robotics (which, to date, has been based only on physical contact) with hands-off assistance. The lack of contact reduces the safety and facilitates integration into clinical practice. These platforms seek to improve patients' involvement in and motivation for treatment because the repetition of the exercises helps their recovery [Okamura et al. 2010]. Many researchers consider the field of SAR to be one of the most ambitious challenges of current rehabilitation robotics [Wilk et al. 2014].

Given the natural tendency of people to relate to all animated entities through social patterns, the effectiveness of social human–robot interaction will be linked to the patient's acceptance of the robot as a trustworthy animated entity. This depends on the physical appearance of the robot but, more importantly, on its behavior [Goetz et al. 2003]. This objective, which manifests itself in our ability to provide personality or intention even to the simplest robots, can be used in rehabilitation robotics to create SAR platforms capable of monitoring, motivating, and encouraging therapeutic activities, thereby improving the quality of the interaction [Tapus et al. 2007b].



Published in [Pulido et al. 2019]

Figure 2.4: Defining Socially Assistive Robotics.

There are different options for creating entertaining activities that provide children with functional schemes that will help them to acquire the motor skills necessary to perform tasks of daily life, i.e., video games, virtual reality, and so on. However, there are works that demonstrate the advantages of social interaction with a physical robot as a way to enrich children's interaction skills and increase their positive emotional responses [Robins et al. 2010, Wainer et al. 2007].

2.3.2 Non-contact Rehabilitation Robotics

Among the most developed and tested SAR systems are companion robotics for the elderly [Wada et al. 2002, Kidd et al. 2006] and a robot coach for stroke patients [Mataric et al. 2007, Tapus et al. 2008]. However, some works in the past decade have been aimed at extending the spectrum of target patients and have developed and evaluated platforms for children suffering from brain injuries, such as CP or OBPP [Malik et al. 2016].

One of the main SAR trends is using robots for coaching. The Kinetron robot uses video game-based activities for rehabilitation (e.g., stepping games, Wii Fit, and Dance Mat among others), but the task itself is not directed by the robot [Kachmar et al. 2014], since the system is not able to react autonomously. Six CP patients aged between four and nine years old tested the platform and reported a positive, engaging experience. Experts have stated that there is potential for using a social robot to encourage active participation in these types of rehabilitation games. Another robotic coach is the QTrobot, which was designed to direct and motivate participants during physical therapy [Rodriguez-Lera et al. 2018]. The feedback provided by the robot can be modulated prior to the execution. The authors present a pilot study with four adults, and they plan to enhance and test the platform with patients in a real scenario. Marko is an anthropomorphic robot, designed with 33 degrees of freedom (DoF) and no hands, to be used with a mobile platform [Borovac et al. 2016]. The authors gave special importance to the conversational aspect, so they opted for the Wizard of Oz technique (i.e., the integration of a cognitive architecture that recognizes the therapist's message and produces an appropriate nonverbal response from the robot). The users interacted with the robot, while in reality it was being teleoperated by the therapist.

There are many SAR approaches with different degrees of success and sophistication. A modern approach for stroke patients is the uBot-5 robot which aims to drive upper-limb physical exercises combined with speech therapy [Choe et al. 2013]. The platform is a humanoid robot, 86 cm tall and 16 kg in weight with speakers and a screen in place of the head where pre-recorded videos and animations of human faces can be reproduced to provide social stimuli. Each arm has 4 degrees of freedom but lacks mobile hands. An expert must teleoperate the robot during sessions. The robot carries out movements to be followed by the patient and gives clues in the speech therapy, but all the results need to be recorded by the experts to evaluate the progression of the patient. Thus, it does not save the time of professionals, who are still necessary to supervise and control the whole therapy.

Using the NAO robot as an SAR platform has become widespread. *Carrillo et al.* propose a work scheme whose methodology includes the stakeholders, who make numerous iterations to improve the prototype during the design process [Martí Carrillo et al. 2018]. The platform did not have any sensors for patient tracking. The behavior of the robot was preprogrammed, and the technician supervised the execution, intervening if necessary. A total of 14 sessions were personalized for nine different patients. The authors evaluated the acceptance of the technology by guardians and experts, who obtained promising results and saw potential applications. The next stage involved developing formal trials that help define the necessary clinical procedures. *Fridin et al.* present an experimental architectural design with some potential scenarios for a SAR platform that focuses on CP patients [Fridin et al. 2014a]. They also included an

RGB-D sensor that captures movement tracking. They established a scenario with three activities and performed a proof of concept with 18 normally developing children and measured their level of interaction. They obtained promising results in terms of positive interactions that encourage using this type of technology in rehabilitation.

The Cosmobot robot was evaluated over a period of 16 weeks with six patients aged 4 to 10 [Brisben et al. 2005]. Although the motivational influence of the device was latent, no objective clinical study was conducted, nor is there continuity in the project. Furthermore, this platform lacks autonomy and requires continuous teleoperation.

Current developments are focused not only on physical but also on cognitive or psychological aspects, e.g., the NAO robot [Tapus et al. 2012] or Kaspar [Dautenhahn et al. 2009], among others, in the treatment of autism. *Greczek et al.* developed an adaptation model to regulate the amount and variety of feedback offered to patients with autism in robotic rehabilitation sessions [Greczek et al. 2014]. In their work, they used an NAO robot in an imitation game (copy - cat) and addressed the problem of feedback adaptation to create a general framework for long-term health behavior coaching. To evaluate the model, 12 participants with autism were recruited and participated in five sessions over nearly three weeks. Although the results showed that the model could not exercise completely due to the unvaried nature of the examples, the authors rely on the technique for long-term studies, even if the model relates to other domains. Feedback adaptation offers indistinctly visual or verbal cues preset by the therapist for each exercise. This work considers important to include adaptation mechanisms related to the physical performance of the patient and not the type of feedback offered, since in the area of motor rehabilitation, each patient has different physical capabilities defined as degrees of mobility in each profile. This means that, e.g., in an imitation game, to determine whether an exercise has been correctly or incorrectly done, each patient has his/her own acceptance thresholds that should be constantly updated during each session.

In this regard, employing robotics for interactive stimulation has strong potential compared to other technologies, especially in relation to children because they have the presence of a real partner [Dawe et al. 2019]. This is of particular importance when treating children because it can encourage more direct involvement not only in the game but also in the activity. However, there are other issues of these platforms that are still in very early stages and present great challenges to the community [Tapus et al. 2007b], such as the autonomous control of human robot interaction in healthcare environments or even the ability to adapt the platform to the patient in the long term.

2.3.3 Evaluation Factors

There are increasingly more robotic approaches integrated in care settings where social interactions occur. Evaluating a SAR platform is a complicated task, since there are many aspects to be measured, from achieving the clinical objectives for which it is designed, to reaching a fluent patient-robot interaction. At the beginning of this thesis, there were hardly any evaluation standards or methodologies for SAR platforms in the literature. And to this day, it is still considered a pending issue for the research community [Belpaeme et al. 2013a]. Most of the works have problems of evaluation continuity and present difficulties to find enough participants for the studies or to prolong them over time [Dawe et al. 2019].

When making assessments, it is important to keep in mind that the perception that humans have of these robotic technologies is different from other computing devices [Kiesler et al. 2004]. SAR platforms evoke more anthropomorphic mental models, that is, users seek similarity to human beings in their form and behavior. Therefore, social robots are mostly considered as partners rather than as work tools.

USUS Methodology identifies different evaluation factors that are involved in these interactions: usability, user experience, social acceptance and social impact [Weiss et al. 2009]. The authors present a theoretical evaluation framework with a user-centered development from human-robot interaction perspective in work environments [Dautenhahn 1998]. This methodology also applies to the clinical practice since it can help to understand how to improve the design and construction of new platforms, as well as to evaluate the medical utility of the tool. USUS deals with the assessment in collaborative human-robot situations and tries to answer a general question: *"if people experience robots as a support for cooperative work and accept them as part of society"*, and thus offer a holistic evaluation perspective.

The USUS methodology focuses on four fundamental factors that are in turn the evaluation objectives that contain a set of indicators. Figure 2.5 shows the USUS evaluation factors and lists each of the indicators that comprise them [Weiss et al. 2009]. The term **usability** refers to the ease of using the evaluated concept [Nielsen 1994]; its indicators are: effectiveness, efficiency, learnability, flexibility, robustness and utility. The second factor refers to the **social acceptance** and responds to the will of the individual to integrate the evaluated system into the daily social environment [Venkatesh et al. 2000]; its indicators are performance expectancy, effort expectancy, attitude toward technology, self efficacy, forms of grouping, attachment and reciprocity.

The third factor corresponds to the **user experience** and relates to aspects of how users use the object evaluated: if users understand how it is used and how they feel when using it [Alben 1996]; its indicators are: embodiment, emotion, human-oriented perception, feeling of security and co-experience. The last factor is the **societal impact**, and evaluates the potential impact of the robot in society [Bornmann 2013]; its indicators are: quality of life, working conditions, education and cultural context.

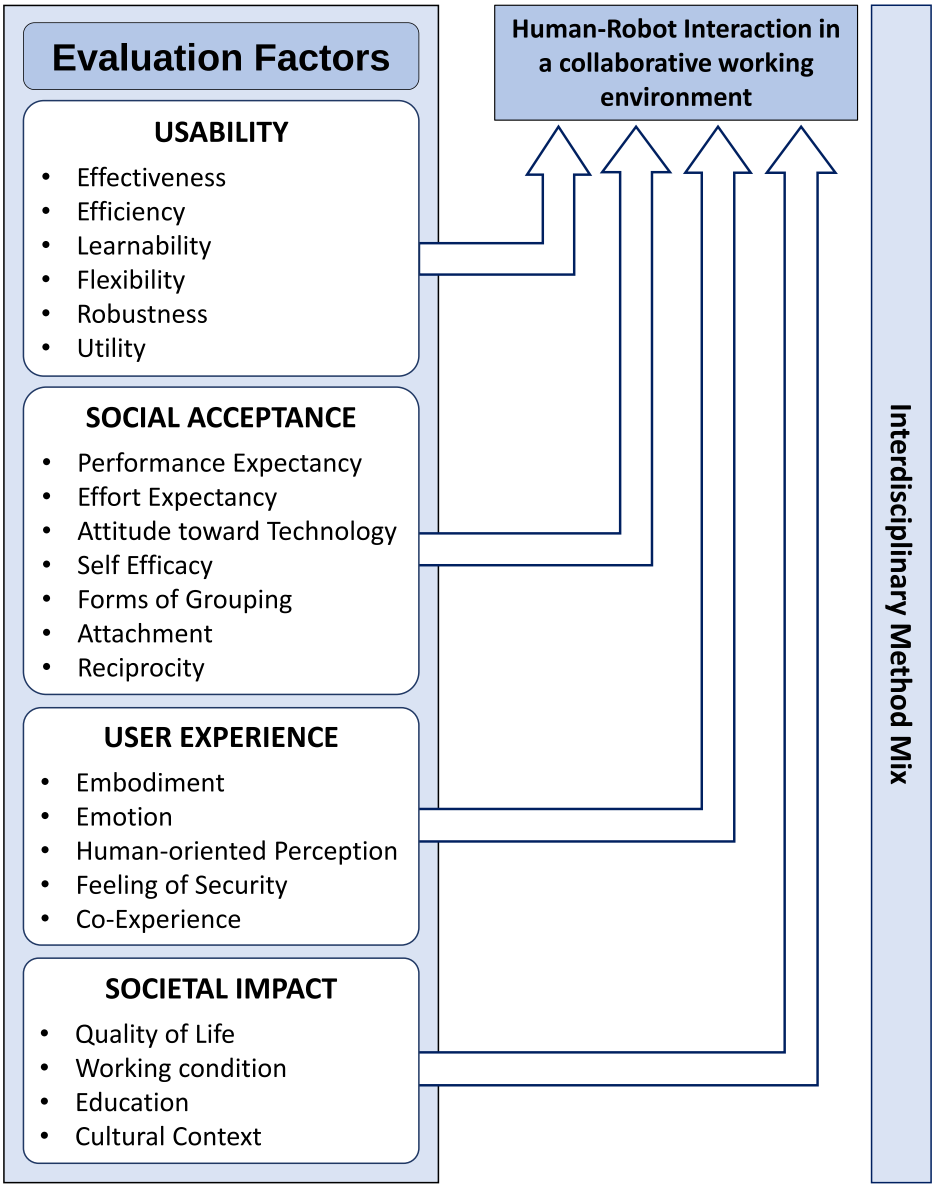


Figure 2.5: USUS Evaluation Framework [Weiss et al. 2009].

Although the authors relate different classical assessment instruments to each of the indicators, including new evaluation mechanisms is a task for the researcher [Nielsen 1994]. Depending on which area or activity is being evaluated, there may be new instruments and evaluation metrics that relate to the factors and indicators of USUS framework.

The main motivation for choosing these evaluation factors is to support the systems whose development and evaluation has focused on the stakeholders' expectations. This methodology facilitates the integration of the all the involved users' results that either interact directly with the robotic platform, or have any type of relationship with it. This leads to multilevel and multiuser evaluations, favoring the contrast of hypotheses from different perspectives.

2.3.4 Ethical and Safety Considerations

A SAR platform provides some kind of service or assistance to human beings through social interaction. Although no physical contact is established between the robot and the individual, these approaches achieve their goals by influencing the human behavior, which brings up multiple ethical and safety issues to consider.

Guaranteeing a safe interaction is the first and main aspect to be taken into account in human robot relations. It is one of the problems that every development must face. Wearable robotics and other approaches that may pose a risk to the physical integrity of people, must meet a series of certifications necessary to put them into clinical practice [De Santis et al. 2008]. In another context, SAR approaches have the advantage of offering a non-contact interaction, so these considerations are reduced to the minimum, although behaving as a social entity that seeks to influence the behavior of individuals, there are other emotional issues that these platforms must comply with [Rabbitt et al. 2015].

2.3.5 Discussion

Robots are starting to cover certain social needs, and progressively integrating into new environments and fields of application, where the human-robot interaction has prominence [Dawe et al. 2019]. The appearance of new needs around the development of devices to improve the response of patients has opened new lines of research in the field of social robotics. The main routes of research aim to take advantage of the social and emotional attributes of these platforms to maintain patient commitment, as well as to motivate, educate, train, communicate, monitor performance, improve healthy habits and provide companionship and support to people [Okamura et al. 2010].

As defined Figure 2.4, socially assistive robotics emerges from the intersection of assistive robotics and socially interactive robotics. This category includes robots that provide assistance through social interaction [Suárez Mejías et al. 2013, Fasola et al. 2010, Choe et al. 2013, Fridin et al. 2014b]. Current trends of SAR seek to accomplish their goals with no physical interaction with the patient [Eriksson et al. 2005]. These robots should be able to move autonomously in human environments, interact and socialize with people. Testing and deploying a SAR platform reduces the safety risk, since it is based on non-contact human-robot interaction. The success of these approaches is given by the emotional bounds between the patient and the robot, improving the motivation to continue with the treatment [Mataric et al. 2007, Dehkordi et al. 2015, Wainer et al. 2013, Boccanfuso et al. 2011, Kozima et al. 2008]. These platforms must deal with a number of challenges [Tapus et al. 2007b, Feil-Seifer et al. 2005a]. On the one hand, a SAR system must really satisfy the needs for it was intended. In other words, these robots must be able to perceive the environment and react accordingly. Otherwise the system may be ineffective at achieving measurable improvements in rehabilitation therapies. A higher level of autonomy implies less human intervention, saving time and effort. On the other hand, verbal and non-verbal communication, voice, feedback and physical appearance are key points in catching the attention of patients and ensuring a fluent interaction.

There is a clear need for development around increasing the autonomy of SAR platforms as a support to pediatric intervention [Dawe et al. 2019]. Numerous shortcomings have been identified in relation to the sophistication of robotic control systems and decision making. Most SAR approaches lack complete autonomy or propose solutions based on teleoperation [Belpaeme et al. 2013a]. The use of the Wizard of Oz paradigm is very recurrent, since it allows to make very rapid developments with evaluations whose interaction is controlled by a human [Marge et al. 2017]. However, the need to teleoperate the interaction does not reduce the time of the clinical professionals, moving away from a real benefit for the health institutions.

2.4 Autonomous Human-Robot Interaction

A SAR platform is considered autonomous when the interaction offered does not require an external operator and its own system solves this process. At the same time, its implementation should be simple, self-explanatory and easy to configure for non-expert users [Feil-Seifer et al. 2005b].

One of the biggest obstacles in the autonomy of the interaction is the selection of actions: execute the most appropriate action according to the state perceived by the sensors [Belpaeme et al. 2013a]. Although one can deduce the expected states that can be reached in each step of the interaction, it is very challenging to return the correct answer in non-deterministic open environments. The mechanisms for selecting actions are frequently implemented with state machines, which are limited when the problem scales in the number of possible actions. There is a representation problem when defining interactive sessions between a human and a robot: what actions can the robot execute to respond to all possible states? There are different representation models that will be discussed in this section, as well as new deliberative architectures for decision making in planning and execution environments. The study of all these solutions will be the key to be able to provide SAR platforms with sufficient autonomy to interact with users without the need for human intervention.

This section extends as follows: Section 2.4.1 starts with a brief analysis of the types of existing control architectures. After this, Section 2.4.2 continues with the definition and formalization of Automated Planning offering the classic and hierarchical paradigm. Finally, Section 2.4.3 explains the PELEA architecture for the autonomous control of human-robot interaction.

2.4.1 Control Architectures

The use of an architecture for Human-Robot Interaction (HRI) is a key point significant to the success of a social robot because an effective HRI platform must solve several complex problems which are very different, yet closely related. Old trends in robotics were characterized by executing low-level actions with extremely high precision, but the current research tries to perform higher level actions with acceptable results. The use of robotic frameworks such as ROS [Quigley et al. 2009] or RoboComp [Manso et al. 2010] to abstract and encapsulate multiple functionalities allows a much simpler integration of all these components and even develop cognitive architectures for robots. These architectures are the essential structure of a domain-generic computational cognitive model [Sun 2001], so they illustrate very well the different solutions used to manage cognitive processes, in spite of the fact that these are not specifically oriented to assistance.

High-level knowledge has normally been represented in a symbolic way. However, there are approaches that integrate a subsymbolic version of the state of the world, which is more similar to the human cognitive experience [Benjamin et al. 2004, Avery et al. 2006, Trafton et al. 2009, Baxter et al. 2013]. There are also specific architectures for rehabilitation which use a mixture of both representations [Prenzel et al. 2005]. The main drawback of these approaches is that subsymbolic knowledge can be difficult to be reused for other solutions, in part because only the symbolic part is directly understandable by humans.

Other architectures are based on different controllers to interact with the robot [Brisben et al. 2005]. Interestingly, some modern approaches continue to rely on simplicity and use fully reactive robotic systems without an explicit model of the state of the world [Dehkordi et al. 2015]. This could be useful for teleoperation or simple behaviors, but the lack of autonomy devalues one of the main challenges of SAR platforms: the capability to take decisions on the next action to be executed in a more deliberative way, without need of human intervention.

Traditional symbolic representation continues to be a significant line of research in effective SAR architectures [Ng-Thow-Hing et al. 2009, Mead et al. 2010, Boccanfuso et al. 2011, Gross et al. 2014, Suárez Mejías et al. 2013]. These approaches use a symbolic representation to drive rehabilitation sessions, but the deliberative part is addressed with finite-state machines. Automated Planning solutions allow increasingly complex states of the world to be managed by changing small parts in the action declaration of the domains [Ghallab et al. 2004]. That eliminates the need to keep a big and coherent finite-state machine because all actions are given by an automated planner.

2.4.2 Automated Planning

Automatic Planning (AP) is a discipline of Artificial Intelligence that was born in the seventies aiming at solving complex problems through plans formed by a sequence of actions, typically for the execution of a robot or other agent [Ghallab et al. 2004]. Automated planning is a deliberative search process prior to execution: starting from an initial state, the planning algorithm must find the set of applicable actions that reach the final objective state or, from now on, the goals. The difficulty of these problems appears when there are multiple goals that interact negatively with each other, that is, the sequence of actions needed to reach each of the goals modifies the state in such a way that it generates conflict with the actions necessary for the other goals.

In AP, the idea is to develop strategies and search algorithms where the motivation is to get planners which are capable of solving any type of problem. When generalizing capabilities are pursued, the ability to adjust the behavior of the planner to specific problems decreases. One of the planners that has obtained the best results and was the winner of the IPC-2008 and IPC-2011 planning competitions[1] was LAMA-2011 [Richter et al. 2011]. This planner was built on FastDownward, a classic planning system that offers a development and configuration environment for the research of search techniques and heuristics [Helmert 2006]. Other planners offer greater expressive power by accepting domains with functions and actions with numerical preconditions, such as the case of MetricFF [Hoffmann 2003]. For example, the CBP planner, built from MetricFF, allows you to associate costs to each of the actions, so that the planning algorithm considers among all the sequences of applicable actions, which generates a plan with lower cost [Fuentetaja 2011].

There are other approaches that use learning strategies or other techniques to decide which is the best set of planners that solves the greatest number of problems: they are called portfolios. In the IPC-2014 planning competition, IBACOP is the winning portfolio that obtained the best results among all the participants in the satisficing track [Cenamor et al. 2014]. In relation to achieve the optimality of the plans, SymBA was the planner with the best results, winning the optimal track of IPC-2014 competition [Torralba et al. 2014], and establishing the reference point in the search for optimal solutions. It is important to note that these competitions have different objectives than those proposed in this work. Although there are robotics domains, the tracks of the competition propose the resolution of problems in deterministic environments where there is no execution. Therefore, the control of the human-robot interaction in a real environment is a domain that is out of the scope of the international planning competition, and that is addressed here. Although there are numerous planning paradigms, such as probabilistic planning, SAT, and so on, this work focuses on classical and hierarchical planning.

[1] http://ipc.icaps-conference.org - Last access: March 20, 2019

Planning Formalization

This AI technique offers a declarative predicate-based representation of the problem in terms of actions, preconditions and effects, which is easily understandable by any non-experienced reader. An Automated Planning problem is represented by two definitions: domain and problem [Ghallab et al. 2004]. The domain definition comprises a pool of available actions, where an action is defined by a set of preconditions, required to be applied, and effects that change the state of the world. The problem definition is a symbolic representation of the initial state of world (starting point) and the goals to be achieved (desired state). The specification of the problem is interpreted by an Automated Planner to generate a valid plan of actions that meets the desired goals while being coherent with the state of the world.

From a formal point of view, a planning task can be defined as a tuple $\Phi = (F, A, I, G)$, where:

- F is a finite set of positive literals. A literal $f \in F$ is composed of a predicate symbol defined over a finite set of objects, $o \in O$. Using the objects in the problem, planners instantiate all predicates obtaining the grounded literals F.
- A is a finite set of grounded actions derived from the action schemes of the domain, where each action $a_i \in A$ can be defined as a tuple $a_i = (Pre, Add, Del)$. $Pre(a_i), Add(a_i), Del(a_i) \subseteq F$, $Pre(a_i)$ are the preconditions of the action, $Add(a_i)$ are its add effects, and $Del(a_i)$ are the delete effects. $Eff(a_i) = Add(a_i) \cup Del(a_i)$ are the effects of the action. Besides, each action a_i has an associated non-negative integer cost, $cost(a)$ (the default cost is one).
- $I \subseteq F$ is the initial state.
- $G \subseteq F$ is a set of goals.

A state s is a subset of positive grounded literals, $s \subset F$, representing the literals which are true in that state. Applying an action a in a state s_i can be defined as $s' = (s \setminus Del(a)) \cup Add(a)$. An action a is applicable in s, if $Pre(a) \subseteq s$. A plan ϕ for a planning task Φ is a set of actions (in the common case a sequence) $\phi = (a_1, \ldots, a_n), \forall a_i \in A$, that transforms the initial state I into a state s_g where $G \subseteq s_g$. This plan ϕ can be executed if the preconditions of each action are satisfied in the state in which it is applied, i.e. $\forall a_i \in \phi, Pre(a_i) \subseteq s_{i-1}$ such that state s_i results from executing the action a_i in the state s_{i-1}, considering s_0 as the initial state I. The cost of the solution is the sum of the action costs.

Typically, to solve a problem with AP, a modeling language represents the knowledge of the problem as a planning domain. On the one hand, the domain is formed by the predicates that define the state of the world and all possible actions. On the other hand, the definition of the problem is an instance of the model where the initial state and the goals are specified. When the predicates that comprise the state of the world meet the preconditions of the actions, they become applicable. When an action is executed, its effects apply changes (adds and deletes) in the state of the world. Therefore, the task of the automated planner is to search the sequence of applicable actions that reach the goals from the initial state.

Planning Domain Definition Language (PDDL) is one of the most used languages of knowledge representation based on first-order logic for classical planning domains modelling [Fox et al. 2003]. PDDL is based on STRIPS [Bylander 1994] and ADL [Koehler et al. 1997], among others. It was created in 1990 with the idea of establishing a standardization of planning languages [McDermott et al. 1998]. It is widely accepted in the planning community and is used in the domains and problems of the international planning competitions. The more modern versions such as PDDL 3.1 offer greater expressiveness to represent knowledge, allowing numerical variables, preferences, derived predicates or temporal constraints.

Figure 2.6 shows an example of the blocksworld problem, in which a robotic arm executes a sequence of operations to order the blocks. In this example, the initial state consists of block A on block B, and the goals or final state to be reached is block B on block A. The actions modeled in this domain are: *pick-up*(x), *put-down*(x), *stack*(x_1,x_2), *unstack*(x_1,x_2), where x, x_1 and x_2 are blocks. One of the possible solutions that the planner would find is: 1.*unstack*(A, B), 2.*put-down*(A), 3.*pick-up*(B), 4.*stack*(B, A). Assuming that all actions are zero cost, this solution would also be optimal.

When modeling the blocksworld problem, the robotic arm is considered as a resource that is only able to hold one block at the same time, so it is needed to represent in the state of the world whether the robotic arm is holding a block or not. A PDDL representation of the `unstack` action is defined as follows:

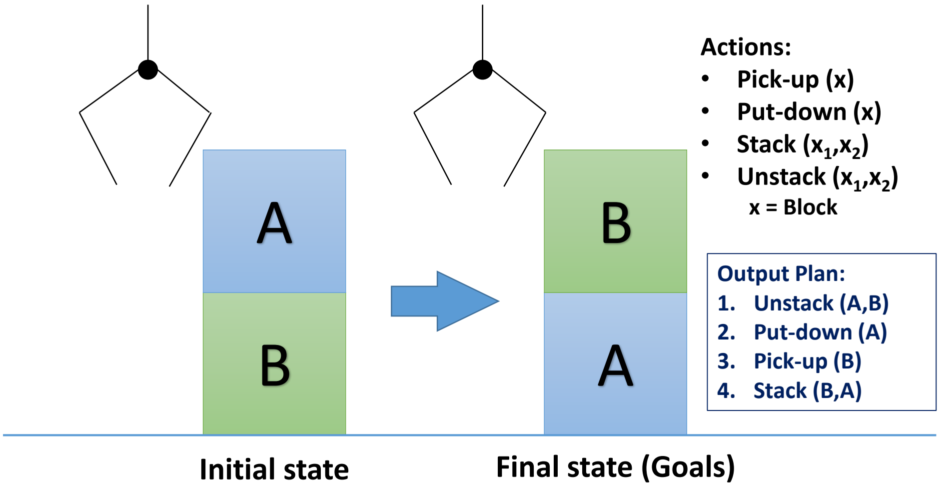


Figure 2.6: Blocksworld problem.

```
(:action unstack
   :parameters (?x - block ?y - block)
   :precondition (and (on ?x ?y) (clear ?x) (handempty))
   :effect (and (holding ?x)
                (clear ?y)
                (not (clear ?x))
                (not (handempty))
                (not (on ?x ?y))))
```

As can be interpreted in the previous model, the necessary preconditions to unstack a block are: the block x must be on block y `(on ?x ?y)`, the block x cannot be held by the robotic arm `(clear? x)` and the robot arm need to be empty `(handemty)`. The effects of applying this action are: the robot is holding the block x `(holding? x)`, the block x is no longer available to be picked up `(not(clear? x))`, the block y is now clear `(clear? y)`, the robot is no longer empty `(not(handempty))`, the block x is no longer on block y `(not (on ?x ?y))`.

The initial state and goals of the problem represented in Figure 2.6 would be defined as follows:

```
(:domain blocksworld)
(:objects A B)
(:init (on A B) (clear A) (ontable B) (handempty))
(:goals (and (on B A) (ontable A))
```

This division between domain, initial state and goals, allows make independent the general knowledge about the problem and each of the instances or cases that can be given. Also, in simple domains with just a few actions, problems of high complexity can be solved. The example explained in this section can be solved easily even by a human being, but in teneral, planning tasks are very hard from a computational point of view (PSPACE) [Bylander 1991].

Classical planning domains are fundamentally aimed at solving plain problems, in which there is a pool of available actions that can be selected regardless of the order between them. In those cases in which there are some constraints of order implicit in the model, the problem should be addressed with other approaches that allow to represent the hierarchical nature of the problem, such as hierarchical planning.

Hierarchical Planning

In those domains that have a hierarchical nature, there are other paradigms where the decomposition of tasks offers more advantages. The Hierarchical Task Network (HTN) is a paradigm of Automated Planning with a completely different approach to STRIPS and PDDL, but following the same premise in the search of plans. The aim is to establish a model based on a hierarchy of compound tasks and primitive actions [Erol et al. 1994a]. The algorithm generates plans from the decomposition of tasks into subtasks until reaching the primitive actions. This decomposition is performed according to the fulfillment of each one of the preconditions of the tasks of the hierarchy. This technique works very well when dealing with problems that can be broken down into simpler tasks and where the problem can be represented as a hierarchy. For example, a therapy is composed in sessions where these in turn can be broken down into phases, each phase into exercises and each exercise into movements.

The planning domains are specified from a set of tasks which can be: A. primitive tasks related to the simple actions of the model, B. compound tasks that are subdivided into other simpler tasks and C. goal tasks correspond to the objectives. Figure 2.7 represents the elements of a hierarchical task network and the relationships that may occur between them. In the tree, a decomposition of tasks takes place until reaching the leaf nodes that are the primitive actions. The relationships between tasks are of two types:

- Hierarchical dependence: establishes a relation of subdivision of tasks.
- Order dependence: a relationship that represents execution order between tasks.

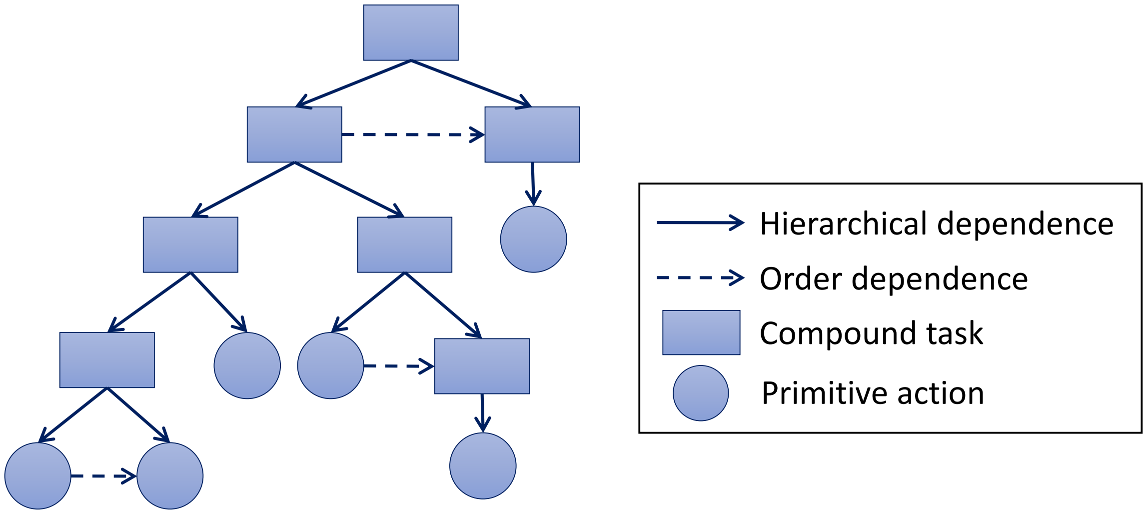


Figure 2.7: Hierarchical Task Network.

The implications of using order relationships as opposed to a hierarchical dependencies is that with a relation of order the search algorithm visits both nodes following this order to check if their preconditions are true. In the case of using only a hierarchical dependence, it is a bifurcation or jump in which the task whose preconditions are true will be executed.

SHOP2 is one of the most used hierarchical planners, developed by the University of Maryland and with great expressive potential since it allows the use of axioms, symbolic and numerical computation [Nau et al. 2003]. SHOP2 also allows to call external programs for operations or comparisons and also supports quantifiers and conditional effects. On the other hand, UMCP is implemented in LISP as one of the most complete planners based on HTN [Erol et al. 1994b]. Finally, SIADEX stands out as a planner with support for temporal constraints that has been used in medical applications as clinical guides or decision support systems [Fdez-Olivares et al. 2006].

2.4.3 Planning Execution and Learning Architecture (PELEA)

Many of the architectures for the control of robots use reactive models that emit a response to the information received by the sensors. These systems have greater difficulties in finding a good solution when you want to solve problems that require a long-term reasoning. This is solved using deliberative models with the capacity to find new plans of actions in the case of perceiving inconsistencies in the state of the world.

The Planning, Execution and Learning Architecture, called PELEA, is a planning and re-planning system that wraps an automated planner to provide the next coherent action with respect to the perceived state of the world [Alcázar et al. 2010]. It integrates planning, monitoring, re-planning, execution and learning modules. It was developed to be a generic architecture independent of the planning paradigm and the actuator or agent that executes the planned actions. Since the effects of the actions may not be carried out, PELEA allows the monitoring of the execution of the plan. This means that it interacts with the external information. If the received state does not match the expected one, it executes a re-planning process to search the solution plan from the received state.

The PELEA architecture was developed in Java and divided into modules that exchange information in XML language. Figure 2.8 shows each of the components that make up the two-level version of PELEA. As external elements are the files of the domain and problem with the initial state to be planned. On the other hand, there is the planner that will be used, for example MetricFF or FastDownward.

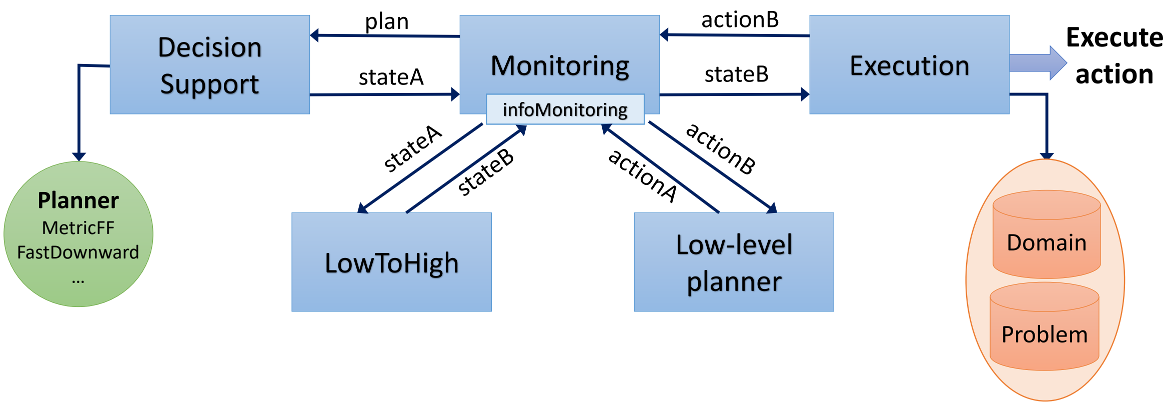


Figure 2.8: Planning, Execution and Learning Architecture (PELEA 2-Level).

The internal modules of the architecture are depicted as follows:

- *Execution* is the module that acts as communication interface with the outside. It receives information about the low-level state of the world and return the next action to be executed.
- *Monitoring* is in charge of monitoring the execution of the plan. It is responsible for checking that the low-level perceived state corresponds to the expected one,

and communicates to the *Decision support* those facts that are relevant. In case of not reaching an expected state, a re-planning process is triggered.

- *Decision support* is the module that wraps and communicates with the planner. It is responsible for deciding which predicates are relevant and should be monitored. In the case of receiving an unexpected state, the replanning process generates a new problem from the current state and calls the planner again.
- *LowToHigh* is responsible for abstracting the information of the sensors to a higher level.
- *Low-level planner* transforms higher level actions into a set of lower level interpretable actions.

PELEA is a general-purpose planning architecture suitable for a wide range of real world applications. This architecture has been used for decision making in planning and execution environments, such as its integration for the control of a wheeled robot (Pioneer P3DX) [Quintero et al. 2011], in a strategy game (StarCraft) [Márquez Colás 2013], generation of parallel actions to control two robots, dodge obstacles, pick up objects, and so on. [2]

In the area of interactive robotics, PELEA has been integrated as a control component in a cognitive architecture for a robotic salesman [Romero-Garcés et al. 2015]. This system has also been integrated as a control architecture in SAR domains for geriatric patients within the framework of the CLARC project [Bandera et al. 2016]. In this project, a social robot conducts comprehensive geriatric assessment sessions, for which it must be able to welcome the patient and relatives, accompany them to the consultation room and, once there, manage all the geriatric test data capture. PELEA is able to control the interaction with the user at all times.

2.4.4 Discussion

A SAR platform is considered autonomous when the interaction offered does not require an external operator [Feil-Seifer et al. 2005a]. In order to be used by non-expert users, it needs to be self-explanatory, easily deployable and configurable. Changing the model or use case is still an open issue, since it requires expert knowledge of modeling [González et al. 2018]. The two main challenges in HRI are to 1) execute the most appropriate action according to the perceived state and 2) the long-term user adaptation [Belpaeme et al. 2013a].

[2] http://www.plg.inf.uc3m.es/pelea/demonstration.php - Last access 06/05/2019

In relation to HRI control techniques, two fundamental lines are distinguished: non-autonomous and totally/partially autonomous. Among the non-autonomous approaches are the teleoperation (Wizard of Oz) [Suárez Mejías et al. 2013, Martí Carrillo et al. 2018] and the scripted behaviors [Kozyavkin et al. 2014, Malik et al. 2014]. In the first case it requires human intervention and the second does not manage the unexpected events that may happen. Those autonomous or partially autonomous approaches are usually based on: symbolic representation [Baxter et al. 2013], in which there is a loss of knowledge in the resulting model, user adaptation based on machine learning [Greczek et al. 2014, Fridin 2014], where many examples are required to converge, and state machines [Roberts et al. 2008], where maintaining coherence when scaling is highly expensive. The use of automatic planning as a deliberative control technique for decision making seems a promising approach in which, through a model (domain and problem), the system can respond to exogenous events that may occur in a session.

2.5 Conclusions

To conclude, this section shows a compilation of the most outstanding works of SAR rehabilitation in pediatrics. Table 2.2 provides a comparative compilation of these works in ascending chronological order. The descriptors of the works are related to characteristics and relevant challenges in SAR that are useful for comparing the different contributions. For each of the works, the characteristics of the participants are detailed (CP: cerebral palsy, OBPP: obstetric brachial plexus palsy, ASD: autism, TD: typically developing children), and whether the SAR platform had the following descriptors: autonomy, perception, adaptation and configuration, it was involved in a long-term study, it was operated in a clinical setting, it offered clinical results and sessions included gamification mechanisms.

The main conclusion is that SAR rehabilitation robotics is still an unexplored area with a lot of work ahead. Most of the platforms in SAR for physical rehabilitation are in an early stage and in many cases, the lack of continuity, makes the prototypes not evolve. According to the comparative compilation, there are no works that explicitly include game mechanics in SAR-based therapies. In general terms, the level of autonomy is very low, with the majority of teleoperated or scripted behaviors. Only 50% of the works have a perception system that introduces real-world data for potential decision making. Regarding the evaluations, there is a few experimental evidence with small samples. There has been no implantation in clinics due to lack of continuity of the works. Only half of them carried out their studies in clinical settings and 3 of them provided longer studies, having more than a proof of concept. Another important detail is that any work provides clinical evidence about the benefits of the platform, that is, there are no results that guarantee that patients improve clinically.

From this previous analysis of the related works and all the needs detected, the development of this thesis focuses on achieving a rehabilitation framework based on social robotics that covers all these indicators, which is clinically evaluated and whose continuity allows a future implantation in the rehabilitation centers.

Authors	Robot	Participant			Autonomy	Perception	Adaptation / Configuration	Long-term	Clinical Setting	Clinical Results	Gamified Sessions
		No.	Cond	Age							
[Brisben 2005]	Cosmobot	6	CP	4-10	✗	✓	✗	✓	✓	✗	✗
[Roberts 2012]	Manoi ATOI	20	TD	18-23	✓	✓	✓	✗	✗	✗	✗
[Rios R. 2013]	LEGO	1	CP	7	✗	✗	✗	✗	✗	✗	✗
[Suárez-M. 2013]	Ursus	6	CP OBPP	3-7	✗	✓	✗	✗	✓	✗	✗
[Kozyavkin 2014]	KineTron	6	CP	4-9	✗	✗	✗	✗	✓	✗	✗
[Malik 2014]	NAO	4	CP	5-14	✗	✗	✗	✓	✓	✗	✗
[Fridin 2014]	NAO	18	TD	4-8	✓	✓	✓	✗	✗	✗	✗
[Greczek 2014]	NAO	12	ASD	7-10	✓	✓	✓	✗	✗	✗	✗
[Adawiah 2015]	NAO	2	CP	5-14	✗	✗	✗	✗	✓	✗	✗
[Rodriguez-Lera, 2018]	QTRobot	4	TD	25-52	✓	✓	✓	✗	✗	✗	✗
[Carrillo 2018]	NAO	9	CP	-	✗	✗	✓	✓	✓	✗	✗

Table 2.2: Compilation of SAR rehabilitation works in pediatrics.

Chapter 3

Design of the Child-Robot Interaction in Assistive Environments

Human beings are able to interact with the environment thanks to their sensory capacity and cognitive processing. Thanks to their evolution, they adapt to each entity, object or person with whom they establish a relationship or contact. The social robotics area focuses mainly on human-robot interaction [Fong et al. 2003]. This line of research attempts to imitate the human beings' behavior while preserving the same principles of interrelation between individuals: social distance, emotions, communication, personality, body language and learning and competence development.

In the Oz or Wizard of Oz paradigm, a human interacts with a robotic platform believing that it is totally independent, while in reality it is being teleoperated by an expert [Marge et al. 2017]. In this case, the interaction is manipulated by a human being and does not require autonomy to behave by itself. However, when the platform must make its own decisions to ensure a feasible and safe interaction, it becomes a great challenge for researchers. Different control and decision making approaches are essential to achieve the proposed objectives [He et al. 2017]. Therefore, a robot must be equipped with a complete set of sensors, which allow it to gather enough external data to make decisions and generate adequate control signals. In order to guarantee a viable scenario during the execution of interaction tasks, it is important to bear in mind that there may be unexpected events, such as failures or abrupt changes in the operating framework.

In assistive environments where a SAR platform is placed at the service of children, the Child-Robot Interaction (cHRI) is defined by the activity that is intended. Therefore, prior to the model design process, it is important to analyze the requirements needed for the subsequent development of an interaction control architecture. Section 3.1 presents a set of compiled principles of design related to pediatric clinical practice, and in Section 3.2, the gamification concept is defined and applied to therapy. After that, in Section 3.3, a general cHRI model is proposed based on three interaction elements: Request-Return-Reward (R^3). According to all these considerations, an autonomous general cHRI framework for hands-off robotics rehabilitation is designed and explained in Section 3.4. This system is governed by a cognitive architecture that controls the interaction offered to the user through a module that integrates Artificial Intelligence techniques for the decision making. In the same way, the framework has motion sensors that capture the information of the environment and actuators that provide social interaction with the users. Tracking the patients' progress is also offered to professionals, while configuring and adapting the session to each patient. It is a SAR-based general framework that can be implemented for its use in the hands-off physical and cognitive therapy process. In order to evaluate the interaction model, Section 3.5 describes the process based on the USUS methodology [Weiss et al. 2009], but applied to SAR-based rehabilitation. It relates the four evaluation factors (utility, social acceptance, user experience and societal impact) with assessment instruments, and these instruments with the possible evaluation phases.

3.1 Principles of Design

Due to the great variability that exists among children, generally due to the differences in their physical and cognitive maturity, it is a real challenge to establish common principles that can define a design for a satisfactory hands-off interaction. Most of these principles arise from the intersection between the literature [Fasola et al. 2013], the interviews with healthcare experts from the Virgen del Rocío University Hospital, and the working methodology of occupational therapists interested in this thesis.

In order to establish standardized treatment guidelines, and according to the clinical protocol explained in Section 2.1.3, there is a set of characteristics and requirements that should be met in all pediatric sessions. These features allow abstracting and generalizing the therapeutic process for both the session design, and the requirements for the session execution, taking into account also the attitude and roles adopted by the social agent. Three categories are identified in the taxonomy: 1) *therapy requirements* focuses on a set of global characteristics that affect the design of the therapy, 2) *therapy execution* proposes a set of requirements to be met during execution of the sessions, and 3) *therapy engagement* determines the fundamental characteristics that the robot must offer to achieve a satisfactory engagement. This taxonomy of requirements is described as follows:

Therapy requirements

The requirements of the therapy establish a set of general considerations that must be present in the design of each of the sessions. These considerations are aimed at guaranteeing the therapeutic goals by proposing a personalized and progressive training for the patient with a playful proposal of activities.

- **Goal-directed**: The execution of the sessions must be oriented to the fulfillment of the clinical objectives established by the clinical professional after the diagnosis. In case these objectives are revised, the sessions should be updated accordingly.

- **Gradual and Balanced**: Both the exercises and the activities proposed in each session must follow a logical progression based on the evolution of the patient. The objectives assigned to each session must cover different areas to avoid overloading the patient's training.

- **Personalized**: The activities that make up each rehabilitation session must be completely personalized and adapted to the condition and capabilities of each patient.

- **Constraint Induced**: The exercises prescribed by the clinical professional should prioritize the training and practice of the dysfunctional part. For example, in physical rehabilitation, an induced restriction therapy restricts the use of unaffected limbs to promote mobility of the affected side. This therapy methodology has shown great results in children with cerebral palsy with Asymetric Motor Impairment [Taub et al. 2004].

- **Game-like Tasks**: The sessions must consist of playful activities so that the patients perceive the task as a game, maintaining a high degree of motivation [Horne-Moyer et al. 2014, Fleming et al. 2017].

Therapy execution

Every session is composed of interactive activities. Each activity consists in turn of a series of requests that the patient has to deal with. The correct performance of the activities will depend on whether or not their supervision is considered necessary. All interaction must respect a comfortable social distance for the patient.

- **Interactive**: Each activity consists of a sequence of interactive elements. An interactive element describes the interaction flow from when the clinical professional makes a request to the patient until he or she completes it satisfactorily. The degree of involvement of the robot in each of the interactive elements, as well as the intermediate interactions necessary until their completion, will depend on the need for supervision of each activity.
- **Supervised**: The supervision of each of the activities will depend on the criteria of the clinical professionals and the needs of each patient. On the one hand, there may be cases in which the patient's autonomy in the resolution of the exercises is valued. On the other hand, the robot platform may support patients in the resolution of activities to achieve a satisfactory outcome.
- **Adaptive**: The SAR platform must have different resources and mechanisms to adapt the sequencing or level of demand of the proposed activities in response to the patient's perceived performance. The objective is to avoid in any case generate frustration or cause injuries to the patient that may later prejudice the adherence to treatment.
- **Adequate Social Distance**: The location and the social distance of the robot are fundamental factors for the interaction to be accurate. In those cases in which the platform also requires displacement, speed is another factor to be taken into account [Michalowski et al. 2006]. It is possible that the distance variable may vary in each case and even more so when working in paediatrics.

Therapy engagement

The engagement is a crucial aspect in neurorehabilitation. It refers to the establishment of a collaborative connection between the patient and the robot to achieve a common goal [Tapus et al. 2007a]. An attitude based on positive reinforcement and empathy is essential to achieve a satisfactory proactive response from the patient.

- **Attention**: In order to achieve an active engagement, the robot needs to maintain the user's attention captured during the interaction. For this purpose, in the first place there must be a constant visual connection between the two so that the process of social interaction can take place. The robot must be able to communicate verbally and non-verbally, both are necessary to establish an attractive interaction [Sidner et al. 2005].

- **Positively Reinforced**: The robotic platform should encourage the positive attitude of the patient through positive reinforcement during the completion of the exercises. Similarly, there must be rewards to encourage the patient's effort, who must be aware of their existence as a way to improve motivation.

- **Promoting Bonding and Empathy**: The robotic platform must convey the feeling of "we" as a team with common goals to fulfill. This therapeutic alliance may lead to an emotional bond. A positive relationship between the robot and the patient is a positive and necessary predictor to achieve good therapeutic outcomes [Keijsers et al. 2000].

These requirements are fundamental ingredients that will are aligned with the design of the interaction model throughout the following sections of this chapter.

3.2 Applying Gamification to SAR-based Rehabilitation

The introduction of game-based activities in physical therapy is given by the qualities offered to its beneficiaries, being attractive and motivating [Janssen et al. 2017]. Although these characteristics may not guarantee compliance with the therapeutic objectives, they serve as a channel to improve learning and influence the behavioral patterns of patients in favor of these interventions. This happens thanks to the rewarding nature of game-like activities, where users release dopamine when they are reinforced by their achievements. This chemical release helps in learning through the long-term potentiation of neurological connections [Bao et al. 2001]. The game mechanisms serve as a tool to clinical experts as an extra layer of motivation and intensity during training. This section aims to bring knowledge about gamification to health professionals and to develop and validate a game-based therapeutic methodology that guarantees compliance with clinical objectives. Similarly, in order to develop specific games for certain groups of patients, game developers need to have enough background to reduce the gap in knowledge between the therapy designers and game designers [Laver et al. 2011].

The main characteristic of gamification is its rewarding character that generates great satisfaction for the user [Richter et al. 2015]. Figure 3.1 shows the four fundamental aspects that define the mechanics of the game:

- Reward, in order to obtain a well-deserved benefit.
- Achievement that refers to the personal satisfaction when meeting a goal.
- Status that allows to establish a more valued social hierarchical level.
- Competition, defined as the desire to compete and to be better than others.

When designing the game mechanics, these aspects should be considered to apply the most interesting strategy. For example, a highly competitive game, where each victory would be reflected in the player's status; or a challenging game, in which each milestone or achievement reached is reinforced by different rewards to the player.

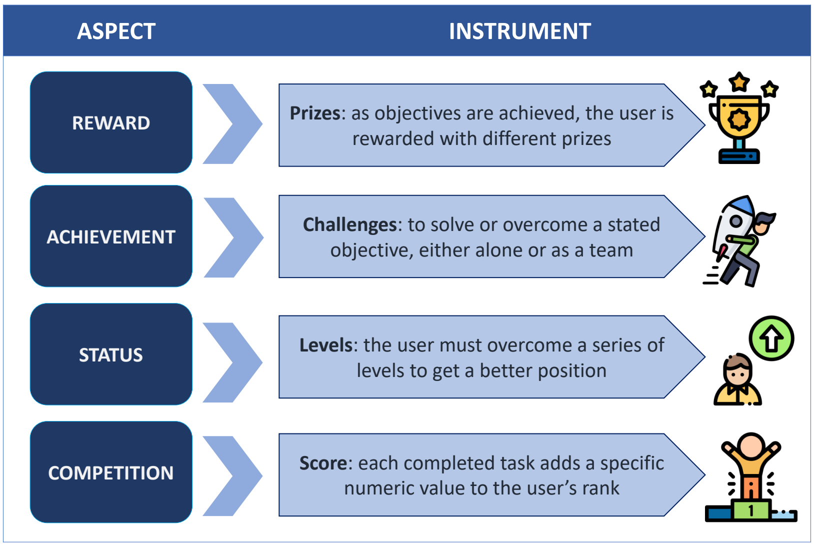


Figure 3.1: Aspects and instruments in gamification.

Figure 3.1 also relates the four fundamental aspects (Reward, Achievement, Status and Competition) with the most commonly used instruments, although an instrument may be related to more than one aspect depending on the perspective. For example, the score is an instrument that directly applies to the competition aspect, but it could also be related to the status aspect, since improving the score may position the user in a better status.

Determining the best or the preferred child learning/training methodology is a difficult task, however, there are works focused on training a set of skills hidden in long-term tasks [Cassidy 2004, Smits et al. 2010]. From the point of view of gaming, this is achieved thanks to the user's immersion in the background of the game. Immersive games are those in which the user learns and develops hidden skills in the game itself without being aware. The user feels involved in a game ambiance so that the emotions he or she evokes are similar to those of real life [Kickmeier-Rust et al. 2007]. The characteristic of immersion in a gamified therapy would guarantee a greater concentration and less distractions on the part of the patient, as well as a greater commitment due to the empathy that he or she feels when being involved in this experience.

In addition to capturing the attention of patients, stimulating them repeatedly is also important. One of the goals of Neuroscience is to know how the brain correlates the lived experiences [Hebb 2005]; so that if two neurons are activated at the same time, a bond between them is established and strengthened [Schacter et al. 1998]. This concept is very promising in the design of the therapy since, during the game, the repetition of specific tasks could be manipulated in order to establish new neurological patterns that favor the recovery of the patient.

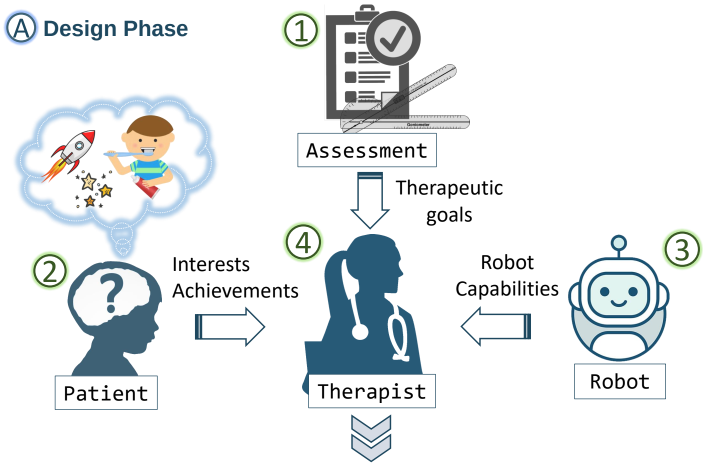
The immersion together with the reward are the main ingredients to get engagement and commitment in a gamified therapy. The rewards evoke the release of dopamine that favors neuroplasticity and therefore the learning of new skills [Bao et al. 2001, Seitz et al. 2009]. Games that reinforce the consequence or achievement of an objective influence much more positively on the learning of the individual [Koepp et al. 1998]. A gamified therapy must have a reward system based on the patient's preferences. It is possible to influence the perspective that the child has of the therapy taking it to a effort-reward point of view much more satisfactory.

Another fundamental aspect is to find the intersection between the therapy design and the game design. It is important to locate those elements that coincide in order to create a direct relationship between both areas. In the case of objectives, the relationship is determined by the concept of "little game" and "big game" in gaming, and sub-goals and main goals in therapy, respectively [Janssen et al. 2017]. "Little game" or sub-goals refer to a set of skills that need to be mastered, as they are subordinated by the main goal. For example, in a game, it can be to learn how to jump, move or shoot; and in a therapy, it could be to get your arms up and grab a certain object. "Big game" or main goal refers to the final goal the patient wants to achieve. Following the previous example, the final objective of the game could be to defend a fortress of hordes of enemies in which it is required to move, jump and shoot to get it. In the case of the therapy example, it could be a functional ability such as combing in a self-sufficient way, so the patient would need to have enough mobility in the arms and be able to hold a comb.

SAR platforms have a motivational potential that is inherent in their own nature [Fasola et al. 2012, Feil-Seifer et al. 2009]. Although the interaction with a social robot is very attractive, it does not guarantee a long-term engagement of patients due to the prolonged exposure of the platform. It is possible that, over time, patients become accustomed and may lose interest in the robot. Children are generally exposed to very complex and sophisticated toys, so that the interest of the child is easily lost when the limits of the robot's responsiveness are discovered [Belpaeme et al. 2013b]. Avoiding this situation is a great challenge for the scientific community [Tapus et al. 2007b]. Therefore, it is necessary to complement these interactive robotics activities with gamification techniques that increase the degree of motivation and produce sufficient commitment to reach the entire treatment.

As previously mentioned, gamification is defined as the inclusion of game mechanics (game-like tasks, instruments and immersion techniques) in non-game environments, as in physical or cognitive therapy. Figure 3.2 depicts an extended gamified therapy framework for its application to SAR. New considerations have been included to the gamification toolkit presented by *Janseen et al.* [Janssen et al. 2017]. In the design phase, therapists are the designers of the rehabilitation sessions. The first point that they have to consider are the specific clinical objectives defined by the physician after the patient's diagnosis in the assessment phase. Similarly, in order to influence the patient's behavior efficiently, it is advisable to explore the interests and hobbies of the patient, as well as to detect their personal goals and challenges, which are typically related to more functional aspects. The third condition of the design phase refers to the SAR platform, therapists must know the specific technology they will use and the capabilities it offers. Each robot presents different characteristics, as well as the possible sensors necessary for the interaction.

The fundamental requirements necessary to design a gamified SAR-based therapy are: 1) therapeutic goals, 2) patient's interests and challenges, and 3) characteristics of the SAR platform.



Aspect	Example / Use Case
Case diagnosis	Infantile Cerebral Palsy (Diparesis) Low mobility range in upper extremities MACS Level III (Handles objects with difficulty)
Child's interests	Science Fiction, Planets and Spaceships
Child's achievement	Gain autonomy for dressing, eating or bathing
Therapeutic goal	Improve the range of mobility and handling objects
Game mechanics	
Game-like activities:	
▪ Little games	- "Mirror game", the patient has to imitate the robot's postures to train proprioception and range of mobility - The robot asks the patient to grasp and show objects with different shapes
▪ Big games	- "Simon says game", the robot asks the patient to use objects related to dressing, eating or bathing
Immersion:	
▪ Narrative	The robot crashes accidentally its spaceship on Earth and does not remember anything. It needs the child's help to return to its planet. Every activity that the robot proposes, will help it to repair the damaged components
▪ Role-play	The robot takes the role of friendly and clueless companion, and acts as an explorer of outer space
▪ Theatrical Prop	Decoration related to space, e.g. a background cloth with stars
Instruments:	
▪ Rewards	The robot rewards the patient after every activity: Robot dance / "Star Wars" storytelling
▪ Challenges	Help the robot to get repair its damaged components through the proposed activities
▪ Levels	Different levels of difficulty for each game
▪ Score	The patient receives score after each exercise

Figure 3.2: Gamified SAR-based Therapy Framework.

With these three ingredients the therapist would be able to complete the aspects defined in the table of Figure 3.2. The first four aspects are related to the diagnosis and interview of the patient to determine the therapeutic goals, as well as the interests and challenges that the patient wants to achieve. The rest of the table contains aspects related to game mechanics divided into three fundamental categories: game-like activities (little games, big games), immersion (narrative, role-play, theatrical prop), instruments (rewards, challenges, levels, score). The example or use case in Figure 3.2 refers to a patient with cerebral palsy (diparesis), low mobility of the upper extremities and difficulties in handling objects (level III of the MACS scale [Eliasson et al. 2006]). The interviews determined that his main challenge would be to gain autonomy in his daily routine to be able to dress, eat and bathe himself. At the same time, their interests are explored and a great fondness for science fiction and space travel is detected. In order to improve the patient's functional capacity, two therapeutic goals are established: the improvement of the upper extremity mobility ranges and objects manipulation.

The therapist must be familiar with the SAR platform: e.g., a 50 cm humanoid robot with 5 degrees of freedom in its upper joints and a RGB-D sensor to track the patient's movements. From these requirements, the therapist in collaboration with the robotics designer, design the game-like activities. In the first place, two "little games" are proposed: "mirror game" or imitation game in which the robot proposes a sequence of postures that the patient has to imitate. From the clinical point of view, this exercise trains proprioception and range of patient mobility. In the second "little game", the patient has to pick up and manipulate a set of objects related to his daily life (comb, toothbrush, shower head). These games are subordinated to the main game or "big game" that pursues more functional objectives. This game is the well-known "Simon says", where the robot asks the patient to use objects of daily life related to dressing, eating or bathing. The therapeutic activities and objectives are implicitly embedded in the expected challenges without the patient being aware of it. Game designers refer as "suspension of disbelief" to describe the state of mind in which the player is aware that it is a game, but is willing to pretend that it is a form of reality [Domínguez et al. 2013].

Within the game mechanics, immersion aims to introduce the patient into a fictitious environment aligned with their interests and preferences, which encourages them to maintain focus and concentration during the sessions. In the example depicted in Figure 3.2, a story is told in which the robot is a space explorer and accidentally crashes its spaceship into Earth. The robot will need the help of the child to be able to repair its body damaged components and its spaceship. The robot will not remember anything at first, but the more help it receives from the patient, the more memories it will share with him or her. This perspective in which the patient is committed to helping his or her robotic friend fosters the bond between both and therefore improves the quality of the interaction.

Regarding gaming instruments, a system is designed to reward the patient after each activity with animations, dances or storytelling. The challenge aspect would be implicit in the game's narrative: "helping the robot repair the damaged components so he can return to his planet". The therapist can design different levels of difficulty for the patient and receive a score after each exercise.

Developing therapy sessions with a social robot may not guarantee an effective commitment to long-term therapy, since overexposure to it may cause the patient to become accustomed and lose the "novelty effect". Maintaining motivation and active engagement is one of the main challenges in child-robot interaction. The gamification aspects defined here are the necessary ingredients to design gamified therapies based on SAR. The proposed framework enhances the current robotic rehabilitation interventions by immersing patients in a game environment that suits their preferences, while meeting their personal goals and challenges.

3.3 Request-Return-Reward (R^3) cHRI Model

Achieving an active and engaging interaction is the main objective of the cHRI models [Belpaeme et al. 2013a]. In healthcare interventions, clinical objectives must be also met. In order to achieve a engaging experience, maintaining the attention and the interest of the child on the robot is very important: constant visual connection and verbal and non-verbal communication.

Robotic interaction with children differs completely from that of adults. The perception a child has of a robot is not an artificial mechatronic device that is controlled by a computer program [Belpaeme et al. 2013a]. Most of the time they attribute these social robots with qualities and characteristics attributed to living systems [Turkle et al. 2006]. Children provide imaginative potential for encounters with robotic agents that is tremendously valuable in exploring how the community can develop technologies and systems for social interaction. On the contrary, in this technological age, children are permanently exposed to highly sophisticated and often intelligent toys and devices, so the interest of this population is easily lost when the limits of a robot's response capacity are discovered. That is why some studies conclude that providing the robot with less complex behavior, but more robust and flexible, are those that produce the best results with these users [Belpaeme et al. 2013b].

In studies of Neurology with animals, Effort-based Reward training has shown to improve cognitive functioning and emotional regulation during challenging events, thus helping to strengthen the mood [Bardi et al. 2013]. Those individuals who had been aware of the reward were 50% more efficient than the rest in solving the task. These studies establish a basis that opens new doors to therapy methodologies. Therefore, we can state the hypothesis that those patients who are aware of receiving a reward for their efforts, will be emotionally more stable and more efficient in the resolution of the proposed activity. In addition to this, Section 3.2 has explained how gamification can contribute to SAR-based therapies and the potential to include reward models in the interaction. The release of dopamine occurs in overcoming challenges and receiving rewards that contributes to improving levels of satisfaction and motivation in the activity [Bao et al. 2001, Seitz et al. 2009]. For this reason, cHRI should always be considered as a positively reinforced model. The robot must always adopt a positive attitude that encourages the patient in the achievement of the objectives and assess the effort and work of the patient. Therefore, empathy must be a present resource throughout the interaction. The patient must perceive his robotic partner and he forms a team with a common goal.

From the aforementioned, Figure 3.3 depicts an abstraction of the interaction model that meets the design requirements of Section 3.1 while considering the principles of gamification of Section 3.2, called Request-Return-Reward or R^3 model. This model describes the interaction flow that is established between the robot and the patient, as well as the three interaction channels that compose it: Request, Return and Reward. R^3 model is an abstraction applied to SAR of an effort-reward learning model.

In the Request channel, the type of petition demanded is determined by the activity to develop. The requests include all those actions of the robot necessary for the patient to understand the task that must be performed. These actions in turn are specific to the characteristics of the SAR platform. The sender, in this case the robot, must have the ability to communicate (verbally and non-verbally) the request to the receiver (patient). The intelligibility of speech, gesture and communication signals of the robot can be reduced for some individuals [Pennington 2008, Robins et al. 2004]. The language expression and comprehension abilities of patients may vary. The ideal

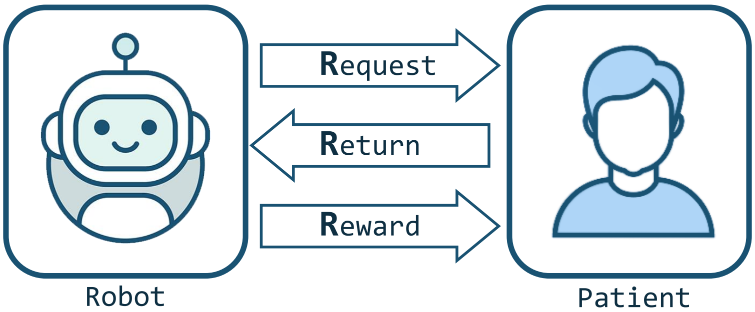


Figure 3.3: Request-Return-Reward (R^3) cHRI Model.

case is to adapt the communication and response times to the capacities of each patient, so that an accessible interaction is offered for different profiles [Qbilat et al. 2018].

Once the request has been made, the Return channel is activated. Here the platform's perception capabilities come into play. The mechanisms of reception can be very varied, from recognition of natural language to artificial vision techniques such as emotion recognition, human behavior understanding or even motion sensor tracking [Kruijff-Korbayová et al. 2011]. The need for these mechanisms is determined by the activity. The information received must be stored and analyzed by the SAR platform to determine the correct achievement of the task. Optionally in this phase and under the criterion of the clinical expert, the robot can monitor and offer verbal and visual cues to help the patient. After processing the perceived information, the Reward channel is activated. According to the Effort-Based Reward model hypothesis, the patient should be aware that he or she will receive a better reward the greater the effort spent. Therefore, the system should be able to measure the performance of each request and reinforce the patient accordingly, so that the best rewards are a consequence of a great performance and are more aligned with the interests and preferences of the patient.

3.4 General Framework for Hands-off Robotics Rehabilitation

Bringing the R^3 model to a non-contact interaction scenario supposes a very high scientific and technical challenge. The first problem is that the user expects the robotic platform to have the same perceptual abilities that he or she has, even though a small fraction of human perception has been reached to date. For example, many advances have been made in speech recognition, but robust models that do not break the interaction flow [Kruijff-Korbayová et al. 2011] are still not achieved. For this reason, in many cases it is decided to "trick" or make the user believe that the platform can see or respond intelligently, using for example the Wizard of Oz technique [Marge et al. 2017]. Another major obstacle concerns decision making. Determining what action to execute is not trivial and most solutions use representations based on state machines with a very poor flexibility given the uncertainty that exists in real environments.

In order to put into practice the considerations discussed above, a general framework for hands-off robotics rehabilitation is proposed. As shown in the Figure 3.4, the two main users that interact with the system are the physician and the patient. The interaction of the physician occurs through a graphical interface that allows to configure the sessions to each patient, monitor the progress and obtain results thanks to a reporting system. The patient is an agent that belongs to the environment or state of the world and interacts socially with a robot, although there may also be other interactive agents involved in the session. For example, in an imitation game, the robot is the main agent that interacts socially with the patient, although the RGB-D sensor would also be an interactive agent in charge of sensing the movements. In general terms, the interactive agents act on the environment or on the patient, while the patient interacts with these agents of the robotic platform. These supporting agents are in charge of gathering information from the environment and interpret this data to provide this knowledge to the rest of the system.

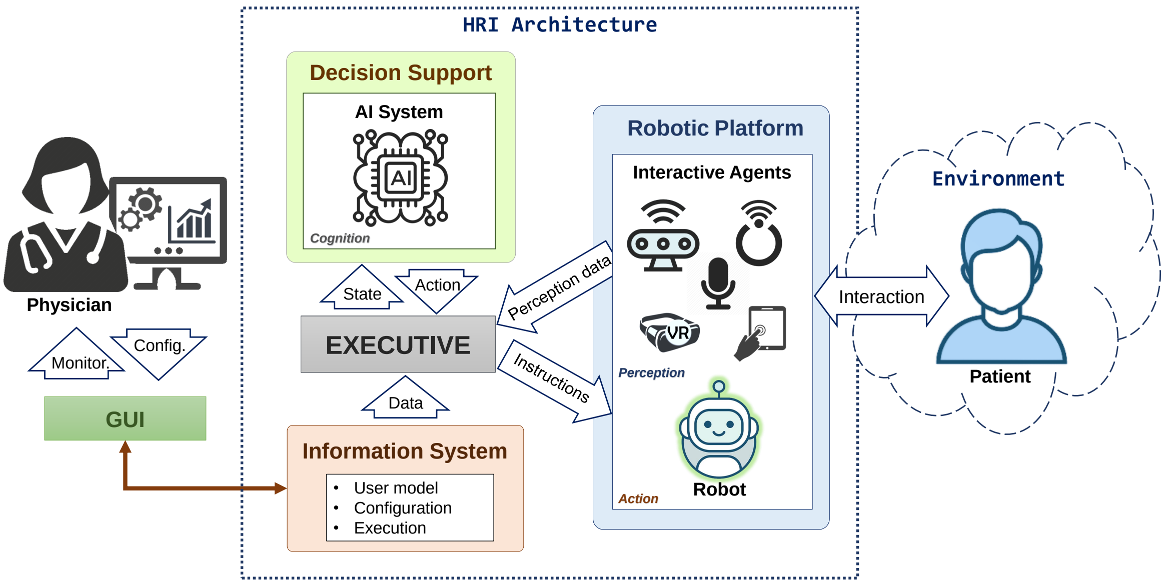


Figure 3.4: General Framework for Hands-off Robotics Rehabilitation.

The robotic system includes the three characteristic levels of cognitive architectures: Perception (sensors), Action (social robot and actuators) and Cognition (decision making). All them are governed by a main module called Executive. The Executive module is the component that directs the use case and translates the perceived raw data into an abstracted state. It also translates high-level actions received from the support system to robot or actuators instructions. This module is fed in turn by the information system that stores data such as: user model (personal data, preferences), configuration (user's objectives and restrictions), execution (internal data necessary for system execution). This general framework offers a closed environment of execution with a strong potential for cHRI. Technologically, it makes possible the introduction of interaction models such as R^3, which comply with the design requirements and principles of gamification studied.

3.5 Evaluation Principles of the cHRI

Determining if the robotic system offers effective interaction is not evident [Belpaeme et al. 2013a]. Many aspects must be evaluated in relation to the cHRI. A fundamental question is to demonstrate whether the interaction guarantees the scope of the proposed objectives or not. In some cases, this may be easy, if the expected results manifest themselves quickly or can be easily measured. For example, in a system that is designed to educate or teach the subject, the effectiveness of the HRI can be determined with the robot's contribution to knowledge gain. However, there are other more complicated domains to measure, such as a robot that offers company. Determining the level of comfort has a high degree of subjectivity. These evaluations are even more problematic when the subjects investigated are children [Belpaeme et al. 2013a]. Unlike adults, children in interviews are complacent with their interviewers, so they always try to find the answer they consider most correct, often choosing the most extreme options. When interviewing children it is essential to take into account that they belong to a category that is very sensitive to faults in the design of the questionnaire [Bell 2007]. Therefore, it is recommended to make a special emphasis and follow the recommendations of the literature, both in its design and administration.

In SAR, there are essential evaluation indicators such as the usefulness of the tool, its social acceptance, the user's experience and the social impact. These four factors are present in the USUS methodology [Weiss et al. 2009], discussed in Section 2.3.3. In the HRI studies, necessary instruments must be administered for their correct evaluation of all these aspects. Figure 3.5 depicts a potential evaluation procedure relating phases and materials with the evaluation factor of the USUS Evaluation Framework for HRI.

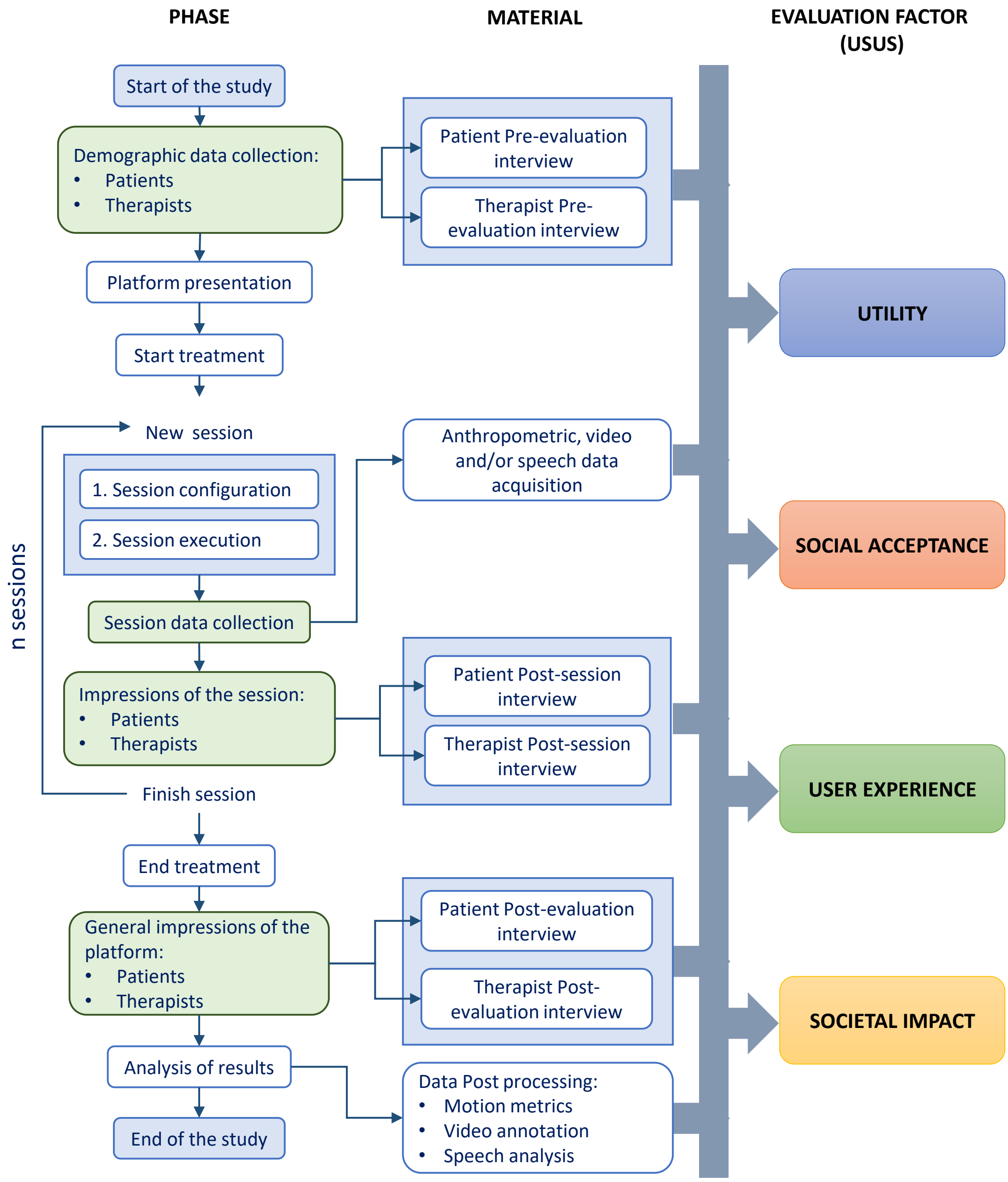


Figure 3.5: Evaluation Procedure adapted from USUS Methodology [Weiss et al. 2009].

The evaluation procedure presented in Figure 3.5 locates each instrument or evaluation material at a certain point in the study. In turn, these materials must be related to the evaluation factors. The same material does not have to contribute to all the factors, but, to have a complete evaluation of a SAR system, covering the four factors at the end of the study is necessary. In the evaluation proposal of Figure 3.5, there are four phases of data collection (colored in green): 1) the demographic data collection through interviews and questionnaires that typically aims to evaluate previous user experience with technology. 2) The data collection of the session can be related to patient's motion data, video recording or speech data. 3) At the end of a session, the intention is to collect the impressions of the patient and the therapists through interviews and questionnaires. 4) Finally, once the treatment is finished, a final questionnaire is administered to gather the general opinions of the complete experience seeking for improvements. Also noteworthy is the subsequent analysis of the data captured from the session using motion metrics, video annotation or speech analysis. This last step aims to include quantitative data to the study that favors the correlation with the opinions of the users. Each material can contribute to one or several evaluation factors, designing the questions of the questionnaire according to the desired aspects is a task of the evaluator. For example, the post-session interview is usually focused on the user experience, while the post-evaluation interview usually has more general questions about societal impact or social acceptance. Utility is a factor covered from the questionnaires, but also from the capture and analysis of session data. Motion metrics or video annotations can yield conclusions that support that the system is useful for the purpose it is designed for.

3.6 Discussion

This chapter addresses one of the main objectives of the thesis: the design and evaluation of a gamified SAR-based framework for hands-off rehabilitation. After the state of the art analysis, the fundamental aspects of the four areas have been detected in an attempt to integrate these elements into the framework design. The overexposure to a social robot may cause the patient to become accustomed losing the perception of novelty. The gathered experience together with the literature support the use of gamification as a motivational incentive [Janssen et al. 2017]. Figure 3.2 depicts an extended gamified therapy toolkit for its application to SAR. All these elements are considered when designing the R^3 interaction model (Figure 3.3) based on effort-rewards paradigms. This poses several technological challenges that are addressed by the general framework for hands-off robotics rehabilitation proposed in Section 3.4.

Chapter 4

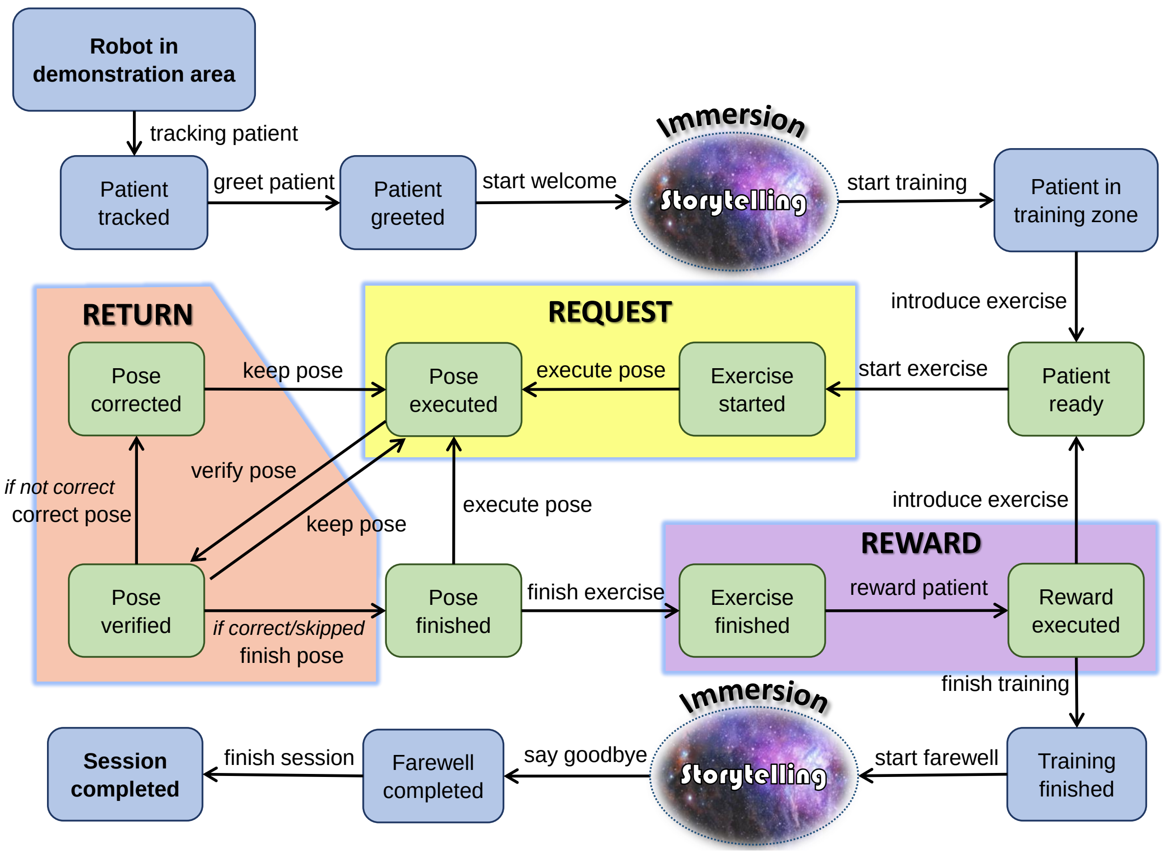
Autonomous SAR for Physical Rehabilitation: NAOTherapist

In line with the objectives of the thesis, this chapter presents NAOTherapist, the first SAR prototype based on the principles of previous Chapter 3 and the therapeutic protocol described in Figure 2.3. This development is motivated by the need to investigate new therapeutic procedures in the area of physical rehabilitation [Calderita et al. 2014b]. From another perspective, NAOTherapist is an instance of the general framework proposed in Figure 3.4. The use case integrates the concepts of the R^3 cHRI model (Figure 3.3), establishing an interaction flow based on "request, return and reward". The gamification in the therapy is also protagonist in NT, making sessions based on games, as depicted in Figure 3.2.

NAOTherapist is a cognitive robotic architecture whose main goal is to develop hands-off upper-limb rehabilitation sessions autonomously with a social robot for patients with physical impairments [González et al. 2017]. The system incorporates a NAO robot as the social interactive entity and a RGB-D sensor to monitor the users' movements. Most of the SAR-based rehabilitation approaches still overlook the autonomy and quick response of the robot which are essential points of SAR platforms [Dawe et al. 2019]. In order to achieve a fluent interaction and an active engagement, the system should be able to adapt itself in accordance with the perceived environment. We consider that during rehabilitation sessions, the lack of human intervention and a fluent interaction promotes an active engagement, in which the robot captures the full attention by being prominent in the room. In NT, this automatic reasoning is carried out using automated planning techniques [Ghallab et al. 2004], where the perceived environment is encoded as a symbolic representation of the state of the world.

4.1 Scenery of Interaction: Use Case

The use case of rehabilitation sessions represented in Figure 4.1 corresponds to the imitation or mirror game, in which the patient must imitate the different poses performed by the robot. Green boxes represent the training stage in which the robot and patient perform the exercises together and blue boxes refer to the welcome and parting interactive stage. The interaction flow of this and every game in NAOTherapist integrates the three main concepts, "request, return, and reward", of the R^3 cHRI model (Figure 3.3). So, in this example, the robot request is defined by asking the patient to imitate the same robot pose, then the return involves those actions related to the pose verification and correction. Finally, the reward element appears when the exercise is finished. Figure 4.1 represents the integration of the R^3 cHRI model as well as the involvement of gamification elements such as immersion (explained in Section 3.2), in an attempt to put into practice the abstract concepts from previous Chapter 3.



Based on the use case published in [González et al. 2017]

Figure 4.1: Execution flow of Mirror Game use case.

The use case starts when the patient enters the experimental room and finds the robot placed in the demonstration area. [1] Then, the system tracks the patient and starts capturing his/her body characteristics. The patient is one or two meters away from the robot in the training area. The robot greets and welcomes telling a story. After introducing the first exercise, the training begins. In the mirror game, exercises consist of a sequence of poses. Depending on the exercise configuration, the patient must maintain each pose for a certain amount of time. The robot is in charge of driving the training process giving instructions and feedback on what to do at each time. Each patient's pose is verified with respect to that shown by the robot. If both poses differ, the system executes a correction mechanism. Patients have two attempts performing a pose correctly: after the first failed attempt, the robot shows the incorrect arm or arms and tells the patient that the pose must be corrected. In the second correction, the robot imitates the detected patient's posture and shows how to move the arms to achieve the correct pose. This is called "mirrored correction". These mechanisms provide helpful feedback to users and help them to get closer to the correct pose. If the patient fails after these two tries, the pose is skipped. The system executes the rest of poses that comprises the exercise sequentially until it finishes. A break is programmed between exercises, when the patient is rewarded by the robot. In these pauses, the robot shows animations, choreography or tell stories to increase motivation after each exercise. Once all the exercises are completed, the training is finished. The robot closes the session with a cheerful farewell, inviting him to play with him again the next day.

The use of automated planning to represent the use case makes easier to change the domain to achieve different therapeutic goals or even different contexts away from the medical model. This flexibility is visible by using the same architecture with other games, such as the adapted Simon game with poses instead of colors [Turp et al. 2019], in which the robot performs several poses in a row and the user has to memorize and perform them to advance to longer rounds.

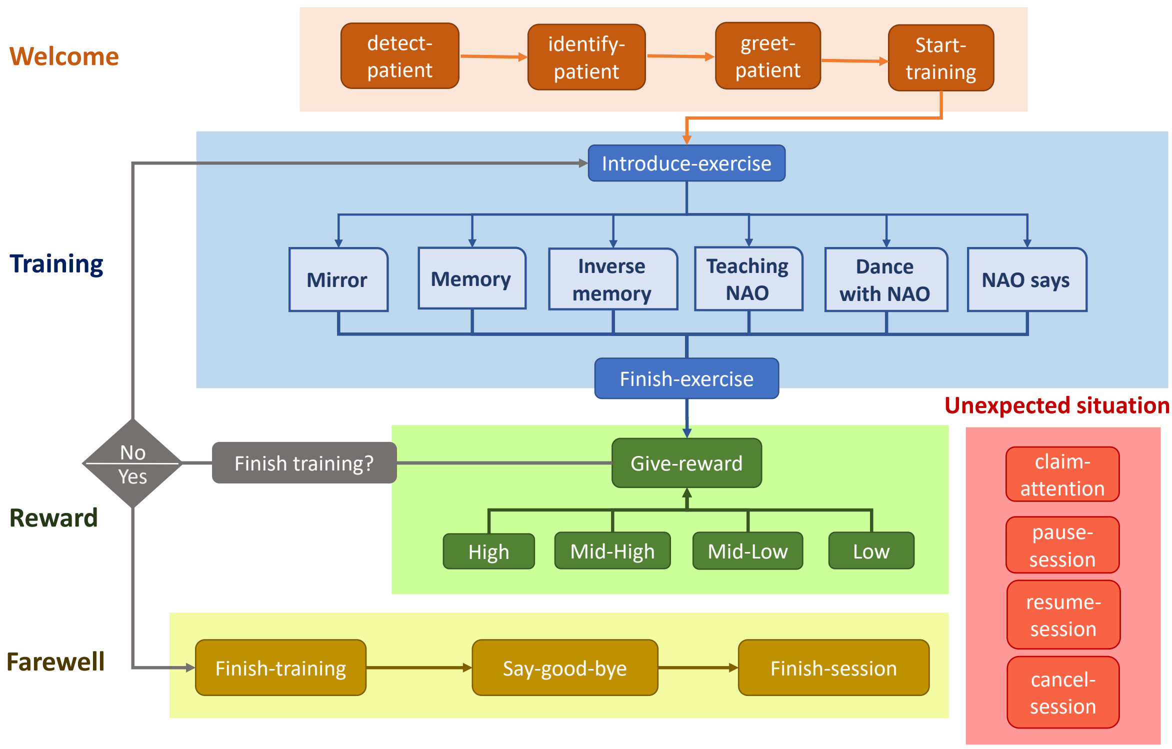
4.2 SAR-based Activities

The NAOTherapist model for game-like activities is expressed by the domain and problem of the planning task. The domain is described in PDDL [Fox et al. 2003], and contains all possible actions that can be carried out in a therapy session. These actions are expressed in a generalized way using variables, such that their definition is

[1] Video of the use case: https://youtu.be/75xb39Q8QEg

independent of the particular activities and poses included in a specific therapy session. Instead of using a different planning domain for every game, we have integrated all new game-like activities with the previous ones into the same planning domain. This allows the planning of every therapy session is performed using the same domain, which provides a robust and flexible solution where the information about all the possible actions involved in a session are centralized in the same domain file.

Figure 4.2 shows the general execution flow of the plan generated by the domain model for a therapy session. It is composed of four main phases: welcome, training, give-reward and farewell. A therapy session always starts with a welcome phase. There are four domain actions the robot performs in this phase: (1) detect that the patient is in front of it; (2) identify who is the patient; (3) greet the identified patient; and (2) start the training, that typically involves some speech acts for indicating that the training is about to start.



Published in [Estévez et al. 2017]

Figure 4.2: General flow of the integrated domain.

After the welcome, the training phase starts. For the training phase, the general execution flow contains an action to introduce the corresponding exercise, the set of actions of the corresponding game-like activity of the session, and another action to finish the exercise. In the low level, the `Introduce-exercise` and `Finish-exercise` actions usually correspond to speech acts. The current game-like activities defined in the integrated domain are: mirror, memory, inverse memory, teaching NAO, dance with NAO and NAO says. The execution flow for these activities will be explained later in the next subsections.

When the training phase is finished there is a give-reward phase that allows to provide reward to the patient after each exercise. This reward can be of different intensity (high, medium-high, medium-low or low) depending on the patient and on his performance of the activity. An example of a high reward is to make a fun dance, while a lower reward would be a simple speech act.

Several game-like activities can be included into the same therapy session. If this is the case, the session does not finish after a give-reward phase, but continues with a new training phase. Otherwise, the execution flow goes to the farewell phase. This is the final phase of therapy sessions, including the actions `finish-training`, `say-good-bye` and `finish-session`. At the low level, these robot actions consist of speech acts and movements associated to these speech acts, as saying goodbye by moving the hand or sitting in a rest position by the end of the session.

"Mirror" Game

In the Mirror game, the robot shows a set of preset postures by the therapist, which the patient must correctly imitate and maintain for a given period of time. While the patient imitates each of these poses, it is monitored that they are performed correctly, with the help of a 3D motion sensor. A common threshold is used for all patients for checking correctness. In case the patient pose is not considered correct, the system directs the interaction to provide instructions to the patient for correcting the pose. There are two more attempts, with two different types of corrections. First, the robot corrects the patient verbally, indicating which arm should be corrected (or both arms if applicable). In the second correction, the robot imitates the patient's posture and shows him how to move the arms from that posture to achieve the correct pose. In this way, each exercise of therapy consists only of a set of poses that the robot shows and that the patient should try to imitate.

"Memory" Game

The Simon game is an adaptation of the Electronic Simon, but using poses instead of colors. This activity consists of the following: the robot performs one or several poses in a row, which the patient must memorize and repeat correctly and in the same order. The difficulty of this game increases as rounds are completed, increasing the number of poses to memorize. This activity works to a greater extent the cognitive side of the patients, in addition to physics, being a good type of exercise for therapies.

"NAO says" Game

Another game designed specifically for hand-arm bimanual therapies is the "NAO Says" game. This game is very similar to the well-known game of *Simon Says*, where the robot takes the role of *Simon* and issues instructions to the child. The kind of instructions given by the robot may consist of touching a part of the body (for example, NAO says *touch your shoulder*), or adopting a basic stance (NAO says *sit down*). In the same way as in the *Mirror* game, if the child does not perform the request correctly, the robot corrects him in different ways until reaching the maximum number of attempts or until he performs it correctly. In the case of touching a part of the body, the child can do it with either hand, since the method for monitoring this exercise checks the distance between the main parts of the body and both hands.

This exercise provides a more cognitive aspect to the therapy. It works to a greater extent verbal comprehension, and planning and sequencing of patient movements. In order to perform this activity correctly, the child must have good body awareness and good proprioception.

"Dance with NAO" Game

Finally, as another novelty we have included the *Dancing with NAO* game. This activity is very similar to the exercise of *Mirror*, but hidden under a greater and distended atmosphere of game, more specifically of dance.

The execution flow of this game is as follows. The robot first tells the child that he is going to teach him a dance. Then, it reproduces the dance choreography completely. After that, the robot teaches the dance to the child step by step. This part of the game is very similar to *Mirror*, since here the robot shows different poses that the patient must imitate one by one. When all different poses belonging to the dance choreography have been completed and the child has learned the dance, the robot asks the patient to try to dance together.

For the point of view of the cognitive aspect, it exercises memory and procedural memory, since the robot performs first the sequence of poses one by one with the aim of carrying out all of them in a row afterwards, similarly to the *Memory* game.

"Teach Me" Game

The *Teaching Me* or *Teaching NAO* game implies a change of roles, in which the patient becomes the therapist showing poses to the robot that it should imitate later. The child is the protagonist of the therapy acting as an active subject and directing the session. In this way, the patient works to a greater extent the executive function of the movements' planning, not just having to imitate another subject. He has to take the responsibility of being a *good* teacher. We expect that having such a greater prominence within the therapy, his motivation and involvement in the exercises increase drastically.

The possible poses that the child can teach are defined in a catalogue. This catalogue is available for both, the child and the therapist so that they can select which pose to teach. First, the robot asks the patient to teach it to perform a new pose, which is supposed to be unknown for the robot. Once the child performs the new pose, advised or not by the therapist, and holds it for a few seconds, the robot identifies that pose as a new one. It is considered as a new pose in the sense that though it was within the catalog of possible poses, but it was not being used in the sessions so far. It is at this moment when the robot tries to imitate the same pose shown by the child. In order to give a certain realism to this situation, a random component is introduced to simulate that the robot fails somehow to imitate the pose, being rather different from the one taught by the child. In case the robot pose is wrong, it realizes of its error. Then, it asks the child to remind him the correct pose again, in order to try doing it correctly again. The same can be done several times in a row, with different poses to teach.

4.3 Sensors & Actuators

NAOTherapist is a robotic tool whose objective is to develop physical-cognitive rehabilitation sessions in a social and interactive way, which helps to motivate patients by stimulating the treatments. For this, the robotic platform consists of a humanoid robot called NAO as an interactive agent that communicates with the patient and a RGB-D sensor for the user's motion tracking. Figure 4.3 shows the schema with the main hardware components of the SAR platform.

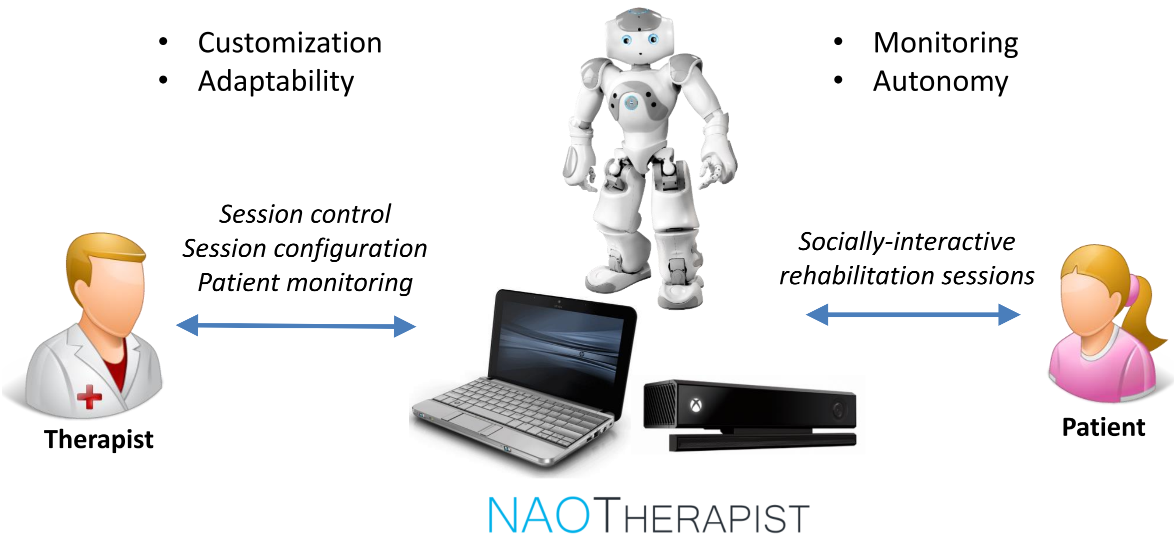


Figure 4.3: NAOTherapist robotic platform.

NAO is a programmable social humanoid robot developed by the Aldebaran Robotics, recently rebranded as SoftBank Robotics [2]. The robot is 58 cm high and weighs 5.5 kg. It has 5 degrees of freedom in each arm and a total of 25 throughout its body. This robot also offers a very complete set of sensors, cameras and microphones, that enhance its autonomous capability, and interactive mechanisms that facilitate to socially interact with people.

The platform also integrates a RGB-D sensor whose main use is to allow users to interact with a robotic system through gestures and movements of their own body. The RGB-D sensor provides both color and depth information. With video data and depth, These sensors are able to identify humans within its range of vision (1.2 to 4 meters) and then, it generates a simplified model of their skeleton. In the version of the sensor used in this work, the skeleton consists of a total of 20 joint points and is able to identify 2 users at the same time.

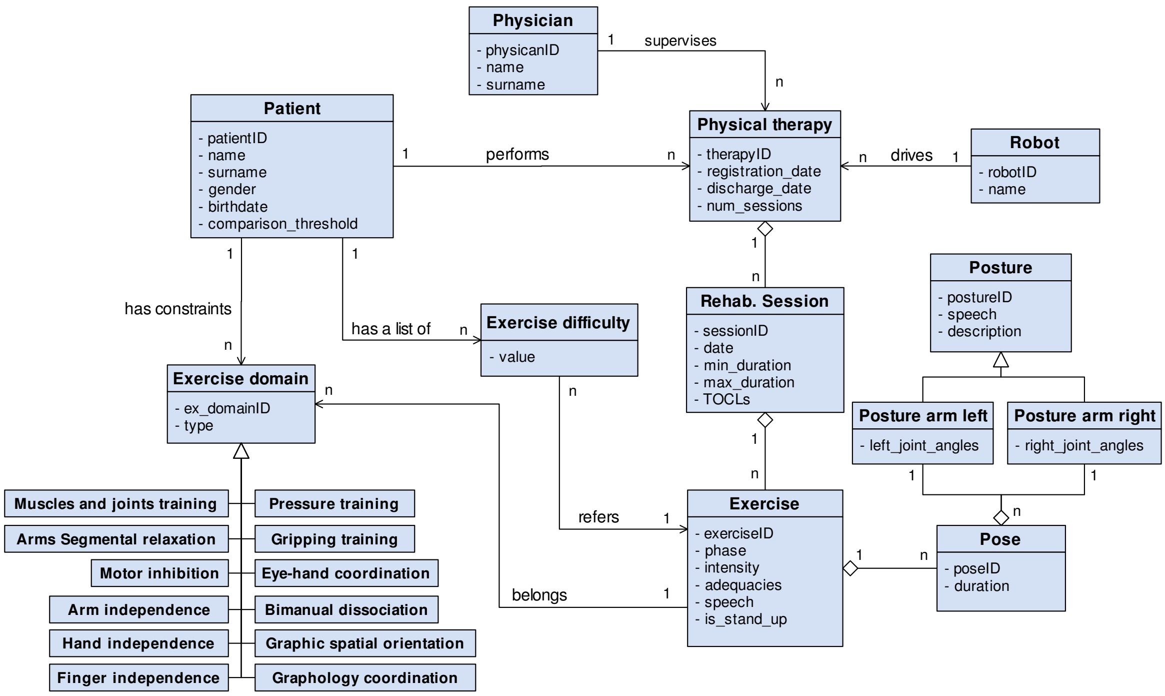
It is important to note that due to the individual design of software architecture components, the platform is independent of the robot and the sensor, so that they can be replaced by other models at any time, requiring very few changes in the software.

[2]NAO webpage: https://www.softbankrobotics.com/emea/en/nao

This has already been demonstrated by evaluating the architecture with other robots and sensors [González et al. 2017]. In the same way, the integration of new actuators and interaction devices is quite simple, since it only involves creating the new component and connecting it with the rest of the architecture.

4.4 Information System

The conceptual model of NAOTherapist, shown in Figure 4.4, is designed according to the project requirements proposed by the clinical experts of VRUH. The ontology tries to join all the clinical concepts with the interaction elements in order to provide a model that contains both parts meeting the project criteria. The conceptual model represents the information that is contained in the knowledge base and it is used by the architecture both in the therapy definition and in the session execution. All exercises and poses of NAOTherapist are designed by physicians and their attributes are defined according to the nature of the exercise and the subjective experience of clinical experts when children are carrying out the sessions. The stored data is crucial for the definition of therapies and the execution of the sessions.



Published in [González et al. 2017]

Figure 4.4: NAOTherapist conceptual model.

Three roles meet in the development of a physical therapy: patient, physician and robot. Following the conceptual model in Figure 4.4, a patient performs a physical therapy that is driven by a robot while is supervised by a physician. These three classes have a unique identification to distinguish the different instances in the knowledge base. The Patient class considers other useful information, both personal and clinical data, such as the comparison threshold that refers to the value that is used as the baseline to compare the poses of the exercises carried out. A physical therapy comprises a number of sessions that take place weekly at the hospital, and each session consists of a group of exercises adapted to each patient. Exercises are modeled as a sequence of poses with a specific duration and the posture associated to both arms. This represents the decomposition from a physical therapy to the order of postures through which exercises of sessions are made up. A posture is defined by a set of joint angles and other attributes, such as speech or description, which improve the interaction with the user. A speech attribute is also considered in the exercise class which is useful in clarifying clearer what the users have to do.

In order to have a more accurate model for the definition of the therapy, the ontology considers which domains of exercises can or cannot be trained by the patient and a value of difficulty for each exercise of the knowledge base. The attributes of a session are useful in determining whether the planned sessions meet the time constraints and the defined therapeutic objectives (TOCLs). It is crucial to have an enriched model of exercises that allows us to determine whether it contributes positively to the training of the patient or not. For this reason, attributes such as "adequacies" can be configured by the clinical experts. They represent a subjective numerical way of how well these exercises are appropriate to the therapeutic objectives of a session.

4.5 User's Motion Anthropometric Model

The NAOTherapist architecture processes the captured data from the RGB-D sensor and generates an anthropometric vision model of the user calculating their range of movements [Pulido et al. 2017], as shown in Figure 4.5. This operation is carried out for each body joint with respect to the anatomical planes (Sagittal, Coronal and Transverse). Joint angles refer to those movements that can be performed by a human body whose center is in a specific joint, and its ranges are defined by the minimum and maximum angles formed by the corresponding joint with its adjacent joints [Kapandji et al. 1988]. So, to calculate joint angles, two segments are created for each pair of adjacent joints, and the resulting angle is calculated between them, using these segments as vectors.

Therefore, to calculate the angles of movements of the human joints, that have multiple degrees of freedom, such as the shoulder, is made through the intersection of the articular segments mentioned above with the normal vector of the respective body plane on which the corresponding movement takes place. All this calculation of the intersection between planes and segments of a joint, can be reduced to a projection of the three dimensions that form the geometric position in just two dimensions. The two dimensions to calculate the projection depend on the referred body plane, removing the 'X' axis in sagittal plane, the 'Z' axis in the coronal plane, and the 'Y' axis in the transverse plane. However, the elbow angle calculation do not need to follow this process. Flexion-extension calculation is made with the two segments, without taking into account the body planes. The elbow rotation is calculated by observing the position of the wrist with respect to the rest of the body, since when rotating the wrist what actually rotates is the elbow.

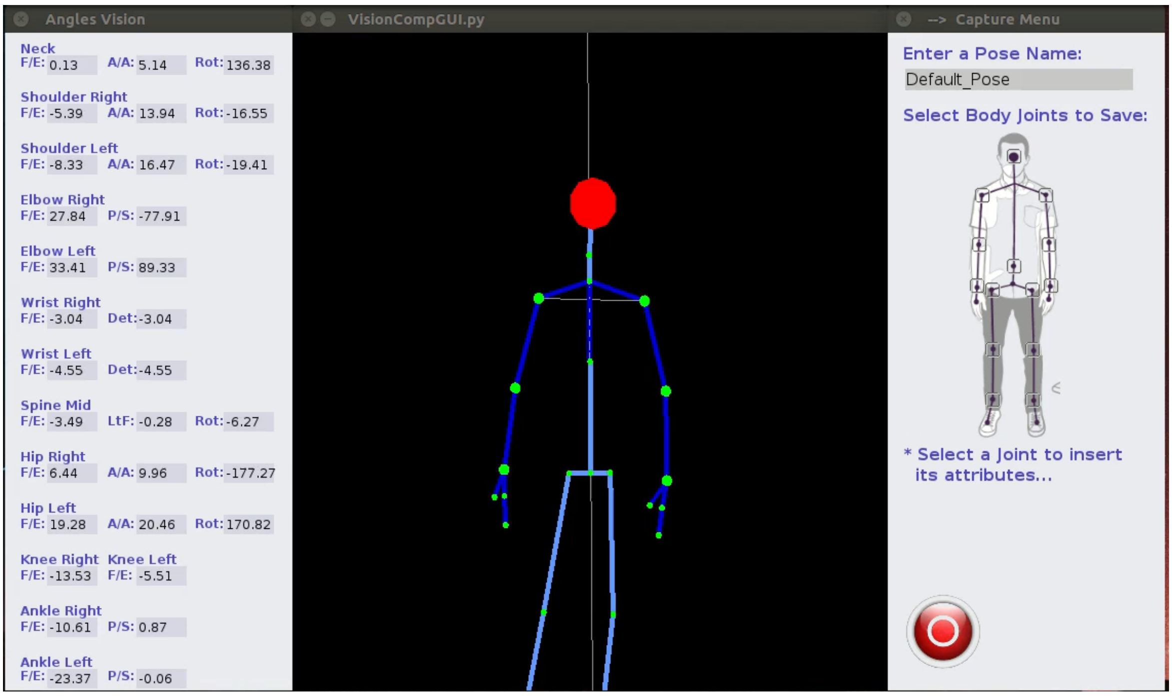


Figure 4.5: NAOTherapist Monitoring System.

The system stores a catalogue of poses based on this angles. This catalogue is used later to compare the perceived users' poses with respect to the expected ones performed by the robot. In this way, the robot can perform different games with the patient. Figure 4.5 shows the monitoring interface. On the left side, all the angles calculated from the anthropometric data of the patient appear. With this, an anthropometric model of the user's poses is obtained, which is much more familiar to the therapists, since the nomenclature of the angles is based on the corresponding associated joint movement. Thanks to the calculation of all these joint angles, one pose can be perfectly distinguished from another, allowing to calculate the distance between two poses.

4.6 Cognitive Architecture

The components of the NAOTherapist architecture have been designed using the RoboComp framework [Manso et al. 2010], which has a development environment, tools and reusable components to control robotic platforms. Each RoboComp component is connected to the others using the Internet Communications Engine (Ice) framework through TCP/IP. The transmission of the data is independent of the language in which the components have been programmed because they use shared Ice interfaces. In our architecture, we have reused one RoboComp component to control a Microsoft Kinect 3D (RGB-D) sensor. It uses the Kinect for Windows SDK to serve the human body characteristics to the rest of the components. The whole NAOTherapist architecture is structured in three levels of planning [González et al. 2017]:

High-level planning is a search–and–selection task addressed using Automated Planning by a component called Therapy Designer [Pulido et al. 2014]. All exercises available in the knowledge base are considered, but only a set of them are included in a session, thus preserving the variability. The planning process is carried out by a Hierarchical Task Network (HTN) algorithm [Nau et al. 2003]. If there are no exercises available to plan a therapy, this model is able to suggest new exercises whose attributes comply with the established requirements and medical criteria.

Medium-level planning refers to the execution of the planned sessions individually, reacting in accordance with the environment perceived by a RGB-D device and the sensors of the robot. A Decision Support component is controlled by the PELEA architecture [Alcázar et al. 2010] which is in charge of planning and monitoring the execution of the exercises and, if required, making decisions with respect to an unexpected perceived state. The knowledge is modeled as a classical planning domain in

PDDL (Planning Domain Definition Language) [Fox et al. 2003] considering the set of actions that the robot can perform in each session and possible unexpected situations. In this way, the robotic platform is able to behave autonomously.

Low-level planning comprises the decomposition of medium-level actions into a set of instructions that are executed by the robot. For instance, moving the arms to a certain pose, changing the eye color, showing animations, etc. At this level the path planner of the robot performs a planning process to move its joints by estimating the trajectories.

4.6.1 High Level: Therapy Definition

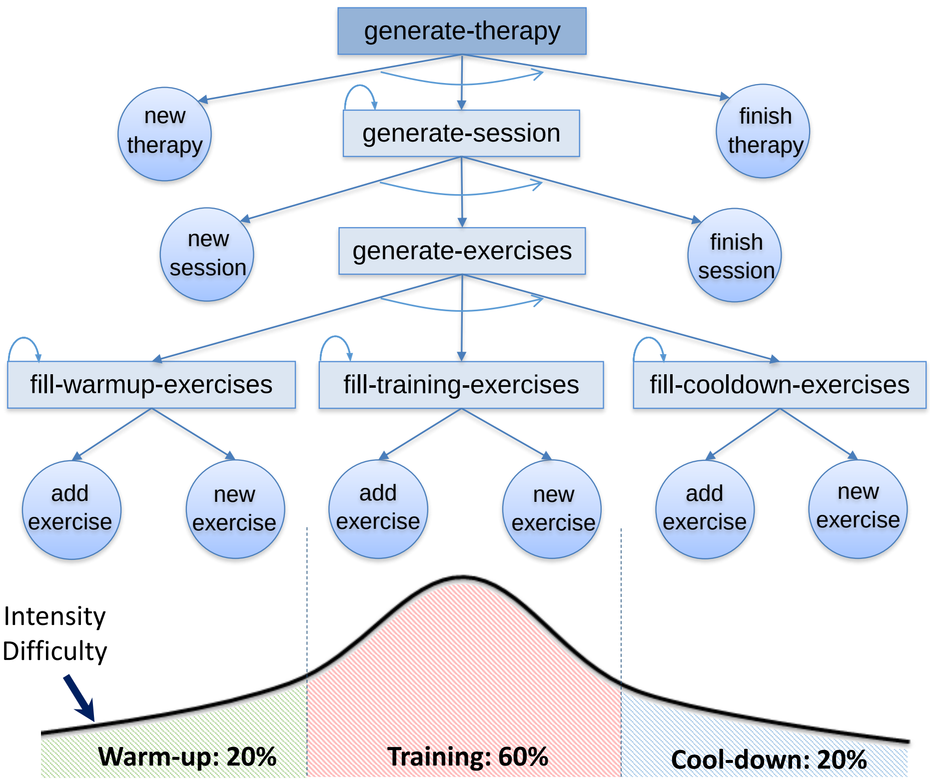
A rehabilitation therapy usually takes place from a set of goals which are decided by the physician based on the degree of mobility, strength and flexibility of the patient. The fulfillment of these objectives during rehabilitation ensures positive outcomes of the patient. As explained in the therapeutic procedure of the hospital (Figure 2.3), therapists are responsible for the manual translation of these objectives into a complete plan of exercises according to the constraints and duration of each session. It is very tricky to find a suitable combination that fits the program achieving the expected levels of training without having a negative response in patients. For this purpose, the model should design sessions whose distribution of exercises are as assorted as possible.

Therapy Designer is a deliberative component based on automated planning that aims to generate therapy plans for patients with obstetric brachial plexus palsy and cerebral palsy. These high-level plans consist of a set of exercises which are then divided into a sequence of poses and subsequently executed by the robot. The system allows as many sessions as configured for the patient to be planned, therefore there may be extensive interactions among sessions due to the variability constraints. The high-level planning is also designed according to the clinical procedure of the VRUH and it is based on an internal guideline of this hospital for the rehabilitation of the targeted patients.

In order to configure the parameters of the therapies, all the information about the patient, sessions, exercises and poses is retrieved from the knowledge base associated to the conceptual model that is shown in Figure 4.4. The patient's constraints refer to those movements or exercises which may cause possible injuries or put the patient at risk. The capabilities are modeled as groups of exercises which can also be restricted to certain individuals. The difficulty and intensity of the conceptual model is a subjective numerical way of representing the exercise features based on the accumulated experience of therapists, that it is used to have a customized definition of the therapies. A rehabilitation session is organized as follows: the initial exercises are for warming up, the most intense ones are carried out in the middle of the session and the final phase is assigned to cooling down and relaxing exercises. Based on the results, the physician can update or refine new details of the therapy.

The therapeutic objectives are represented as cumulative levels which must be reached to achieve the planning goal. According to the clinical guidelines, the conceptual model considers five objectives to be trained: bimanual, fine unimanual, coarse unimanual, arm positioning and hand positioning activities. In the planning problem, these clinical objectives are modeled with five values which represent the training priorities that a patient has for each session. These objectives are called *Therapeutic Objectives Cumulative Levels* (TOCLs) and are established for each session, so they can be updated for future sessions in accordance with the progress of the patient. Achieving varied sessions is an important point to avoid disengagement and boredom while training. This feature is implicit in the model, so that there is a penalty for those exercises which have been previously included in other sessions.

The automatic therapy generation is correctly addressed in a hierarchical way due to the natural hierarchy of the problem. For this reason, an HTN approach is an appropriate technique to model the design of the therapies [Pulido et al. 2014]. This proposal aims to provide a more easily extensible and configurable model in which expert knowledge can be included at any time. The methods and primitive actions of the hierarchical model are represented in Figure 4.6, in which a therapy is a set of multiple sessions which in turn are broken down into three phases: warming up, training and cooling down. Each phase is completed with suitable exercises from the knowledge base according to its intensity and difficulty, which are expected to be distributed like a Gaussian-like function. The division between phases is given by axioms to represent the duration of each phase depending on the maximum and minimum time of the sessions. There are also axioms to decide the suitability of the exercises to each phase in order to decide whether they are candidates to be included or not. Figure 4.7 shows the different numerical attributes that comprise the *e0* example exercise in HTN code. Two categories of attributes can be distinguished: A) those which are related to the constraints of the problem and B) those which refer to the TOCLs. Group A consists of the duration of exercises which is given in minutes, the intensity and difficulty established from 0 to 100 according to how tough the exercise is and the group of



Published in [González et al. 2017]

Figure 4.6: The HTN model for therapy generation. Circles represent the primitive actions and rectangles refers to the methods of the model. The hierarchical decomposition is modeled with high-to-low arrows and the order relationships are represented with an horizontal curved arrow.

exercise referring to the associated trained capabilities. In the case of B attributes, they are the adequacy levels to the TOCLs, which are a representation of how well this exercise contributes to the therapeutic objectives. This contribution is defined as an integer from 0 to 3. The total contribution to the TOCLs in a session is calculated as the sum of all adequacy levels of the exercises included. Thus a valid therapy plan is one whose total contribution reaches the TOCLs established for the session. If there are no exercises available to be considered in knowledge base, the model allows a plan to be achieved in which it suggests creating or learning a new exercise whose attributes are planned according to the requirements of the session while ensuring the reachability of the TOCLs.

The planning algorithm follows the hierarchical decomposition while respecting the order relationships until reaching primitive actions. A therapy plan can comprise more than one session, so this is also considered in the hierarchical approach and

```
(exercise e0)
(e-duration e0 1.3)
(e-intensity e0 60)
(e-difficulty e0 70)
(e-group e0 g_train_muscles_joints)
(adqcy-bimanual e0 1)
(adqcy-fine-unimanual e0 0)
(adqcy-coarse-unimanual e0 1)
(adqcy-arm-positioning e0 2)
(adqcy-hand-positioning e0 0)
```

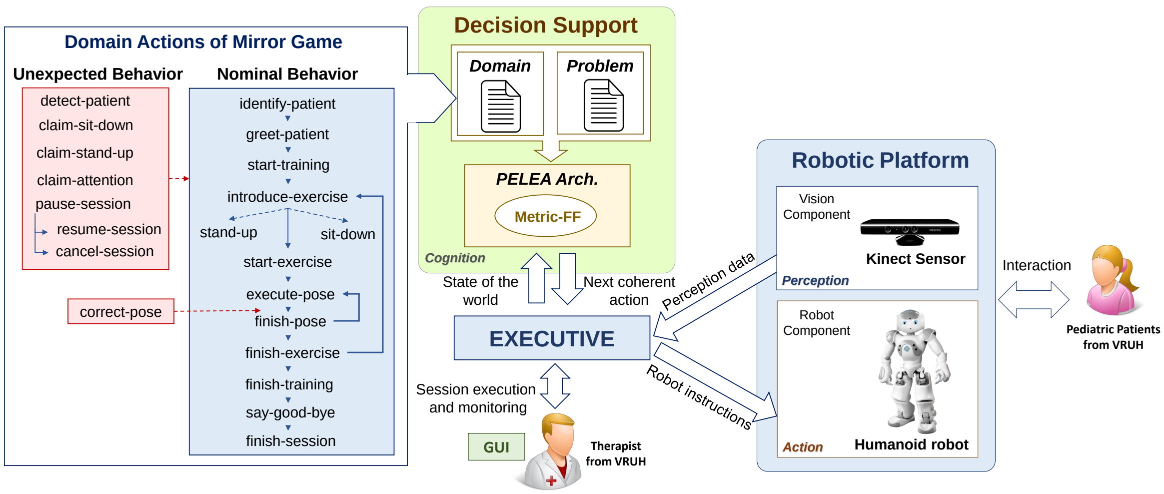
Figure 4.7: Example of the HTN model of the exercise $e0$ retrieved from the knowledge base.

represented in the model by a loop arrow (Figure 4.6). Once the algorithm is in the process of completing a phase with exercises, the planner has to select those suitable according to the phase and variability constraints. However, this blind selection can be inefficient in more complex problems, in which TOCLs are tightly adjusted, since the total contribution of the exercises is not considered until reaching the total time of the session in the last phase. For this reason, a heuristic function (Equation 4.1) is proposed to drive the exercise selection process. This function returns a heuristic value that is calculated before every exercise inclusion. The first term of the summation evaluates the suitability of the exercises to the TOCLs, where d_i is the distance (minus operation) between the current cumulative level, assuming the exercise is included, to the established TOCLs for the planned session. The second part of the equation represents a penalty for the previously used exercises (ex_{times_used} is the number of times an exercise has been included in the set of $num_{sessions}$ sessions). So, the proposed function rewards those exercises whose contribution minimizes the distance to the frontier solution. This allows the selection of exercises to be driven to reduce the number of steps, instead of a blind selection which can cause many backtracking steps to find a valid plan. The evaluation of the therapy designer can be found in Appendix A.

$$ht_{ex} = \sum_{i=1}^{n_{objectives}} \left(\frac{1}{{d_i}^2 + 1} - \frac{ex_{times\_used}}{num_{sessions}}\right) \tag{4.1}$$

4.6.2 Medium and Low Level: Session Execution

NAOTherapist is a cognitive software architecture which provides a socially assistive robot with enough autonomy to carry out interactive rehabilitation sessions. The executed robot actions are coherent with the perceived environment while meeting the session requirements. This study involves two games: Mirror and Simon described later. Both were designed by healthcare professionals experts in the rehabilitation of these patients. In the sessions, the robot performs a set of prescribed poses, which the patient has to imitate. To do that, the robotic platform is supported by a RGB-D sensor, that allows to check the pose of the patient. The robot provides with visual and verbal cues to help patients to correct their posture. The system also incorporates rewards to reinforce patients with dances and animations after every well-executed exercise.



Published in [Pulido et al. 2019]

Figure 4.8: Architecture overview that represents data flow between all components and the interaction with the users (patient, therapist and engineer), as well as the available modeled actions of the domain of the Mirror Game.

The architecture overview is shown in Figure 4.8, where the main system components are represented together with the data flow they shared, and the interaction with the users: patient, therapist and engineer. The patient is the main beneficiary of the therapy and who directly interacts with the robot. This is a two-way interaction channel to provide the patient with instructions and feedback while keeping them tracked all the time. The therapist interacts with the platform in order execute and monitor the sessions through a basic graphical interface. In order to personalize every session, the therapist makes a selection of exercises suitable for the patient's profile This configuration is sent to the engineer, who updates the platform remotely before carrying out the session. It should be noted that the engineer does not take part during the execution at any time, he is not even present, since the decision making is carried out autonomously. The rest of the architecture components are properly referenced and explained in the following sections.

Autonomous Decision Making

In order to achieve a fluent and more natural interaction between the patient and the robot, the system behaves autonomously being controlled with Automated Task Planning, an Artificial Intelligence approach [Ghallab et al. 2004]. This technique offers a declarative predicate-based representation of a rehabilitation session in terms of actions, preconditions and effects, which is easily understandable by any non-experienced reader. So it makes easier to extend the platform with new activities or games. This knowledge representation is modeled as a classical planning domain using the Planning Domain Definition Language (PDDL) [Fox et al. 2003]. An Automated Planning problem is represented by two definitions: domain and problem. The domain definition comprises a pool of available actions that the robot is able to execute, where an action is defined by a set of preconditions, required to be applied, and effects that change the state of the world. The problem definition is a representation of the initial state of world (starting point) and the goals to be achieved (desired state). The specification of the problem is interpreted by an Automated Planner to generate a valid plan of actions that meets the desired goals while being coherent with the state of the world.

In the NAOTherapist architecture shown in Figure 4.8, the task planning process is carried out by the Decision Support component, which includes a planning, monitoring and execution sub-architecture for real-time applications, called PELEA [Alcázar et al. 2010]. PELEA is a planning and re-planning system that wraps an Automated Planner (Metric-FF is used [Hoffmann 2003]) to provide the next coherent action with respect to the perceived state. This state is built by the Executive Component from the perception data received from the Vision component. This action is decomposed into robot instructions by the Executive component and sent to the Robot component to make the appropriate call to the robot.

Since this is a non-deterministic environment where unwanted events may occur. When modeling the domain, two types of behavior need to be considered: on the one hand, the nominal or desired behavior refers to the flow of actions that define an execution that conforms to what is expected. On the other hand, the unexpected behavior focuses on those actions that are activated exogenously through the perception data. In other words, the initial plan would be defined by the desired nominal behavior, in case that something unexpected happens, the decision support component will detect an inconsistency between the expected and the perceived state of the world, and therefore the plan will cease to be valid. Then, PELEA would execute the replanning mechanism to search the necessary actions that solves the conflict. For instance, from the actions of the Mirror game represented in Figure 4.8, if the patient is not able to imitate the pose of the robot after executing "execute-pose", the motion capture system will detect and notify it to update the state of the world in accordance, returning the action "correct-pose" that gives the patient the appropriate feedback.

4.7 Reactive Behaviors

This section presents the reactive behaviors of the robot that are launched at a low level. Among them are the method of comparison of poses, the mechanism to give feedback to the user and the reward system.

4.7.1 Pose Comparison

The state of the world is an abstraction of the environment in which the robot works. This is modeled as a classic PDDL automated planning problem and describes the environment using predicates and functions. Some of these predicates control transitions between actions and are only changed internally by the effects of the planned action; but others are changed by external events (exogenous predicates). For instance, the values of the predicates *patient_detected* and *correct_pose* are obtained externally from the sensors. The recreation of the actual state of the world requires data to be captured from the sensors and to infer visual information in the Vision component to decide the value of the exogenous predicates.

The Vision component provides methods to the Executive component, in order to return the externally-processed information captured by the RGB-D Sensor component. These methods address the following two aspects: pose comparison and situation awareness.

Pose comparison uses an estimation of the anthropometric model of the user provided by the RGB-D Sensor component and calculates the angles between joints with respect to the anatomical planes for each arm. The system stores each pose in a knowledge base as static 3D skeletons to compare them with the ones provided by the 3D sensor and to move the robot accordingly. Then, the method calculates the difference between the joints of the desired pose and the patient's performed in terms of the normalized Euclidean distance. Given the angles from joints a_i where $i = 1...4$ and $a_i \in \{$shoulder rotation, shoulder opening, elbow rotation and elbow opening$\}$. The distance $d(a^h, a^r)$ is computed and normalized between 0 to 1 following Equation 4.2. The closer the difference is to zero, the more the patient will be approaching the correct pose.

$$d(a^h, a^r) = 1 - \left(\frac{1}{1 + \sqrt{\sum_{i=1}^{4} (a_i^h - a_i^r)^2}} \right) \tag{4.2}$$

Given $d(a^h, a^r)$, the patient's pose is correct if $d(a^h, a^r) <= \theta$ (threshold) and is incorrect otherwise. This adaptive threshold θ takes values from 0.28 to 0.4. Both bounds were calibrated experimentally by the therapists for this purpose. The lower bound represents the strictest value to be compared with the $d(a^h, a^r)$, so a more accurate imitation is needed, while the upper bound is the most permissive value. In every session, θ is initialized to 0.28 and is updated after evaluating the success of the patient throughout the game. The system offers three attempts for every imitation, otherwise the pose is skipped. In this case, θ is increased a 2%. In contrast, when the patient performs correctly a pose on the first attempt, the threshold is decreased a 2%. These values were previously calibrated by the experts. This explains how the system behaves being more permissive or not according to the performance and success of the patient during the session.

It is important to note that a pose is accepted if it is maintained for a determined amount of time. The duration of a pose is established by the therapist according to the configuration of the exercise, so several comparisons are needed in order to accept a pose or not. There will be one comparison per received video frame. When the system is checking the pose, it takes and compares as many video frames with 3D skeleton data as the system can handle, as can be seen in Algorithm 1. The greater amount of samples, the more accurate check result. This explains the need of having a fast-to-calculate equation (Equation 4.2) to determine a correct pose.

Algorithm 1: Check Pose.

```
Input: Pose, Duration, Threshold
Data: MaxTimeToStart, MinCompsToStart, MaxFailProportion
Output: Checking result
// 1st: Waiting first correct comparisons
EndTime ← MaxTimeToStart+CurrentTime();
NumCompsOk ← 0;
while NumCompsOk < MinCompsToStart and IsPatientReady() and
 CurrentTime() < EndTime do
    Comparison ← CompareCurrentPose(Pose);
    RobotSetEyeColor(Comparison, Threshold);
    if isValid(Comparison, Threshold) then
        NumCompsOk ← NumCompsOk+1;
    else
        NumCompsOk ← 0;
    end
end
if CurrentTime() < EndTime then
    return PatientNotReady;
end
if NumCompsOk < MinCompsToStart then
    return GetLastIncorrectJoints();
end
// 2nd: Checking throughout the pose duration
EndTime ← Duration+CurrentTime();
NumCompsOk ← 0;
NumCompsFail ← 0;
while IsPatientReady() and CurrentTime() < EndTime do
    Comparison ← CompareCurrentPose(Pose);
    RobotSetEyeColor(Comparison, Threshold);
    if isValid(Comparison, Threshold) then
        NumCompsOk ← NumCompsOk+1;
    else
        NumCompsFail ← NumCompsFail+1;
    end
end
// 3rd: Returning results
if CurrentTime() < EndTime then
    return PatientNotReady
end
NumCompsTotal ← NumCompsOk+NumCompsFail;
if NumCompsFail/NumCompsTotal > MaxFailProportion then
    return GetLastIncorrectJoints();
else
    return PoseOk;
end
```

Firstly, before starting to measure the duration of the pose, the system waits a maximum of 4 seconds for the patient to pose correctly. This requires 3 consecutive valid comparisons to avoid possible false positives with the 3D sensor. When the patient starts the pose correctly, the system triggers the timer for the pose and carries out as many comparisons as possible, counting failures and successes. Finally, the pose is accepted if the number of failures is less than the 20% throughout the total duration of the pose. In the case that the pose is incorrect, the function getLastIncorrectJoints() returns the last three comparisons to determine the limb or limbs to be corrected (left, right or both), giving the appropriate verbal feedback.

The "dynamic-comparison threshold" θ takes values from 0.28 to 0.4, which have been determined experimentally by the therapists. The minimum represents the strictest value to be compared with $d(a^h, a^r)$, so a more accurate imitation will be needed, while the maximum is the most permissive. In every session, θ is initialized to 0.28 and is updated after evaluating the success of the patient throughout each pose. As can be seen in Algorithm 2, the system allows three attempts (with two different correction types) to carry out a pose correctly, otherwise it is omitted. In this case, θ is increased by 4%. In contrast, when the patient performs a pose correctly at the first attempt, the threshold is decreased by 2%. These percentages determine the speed of the evolution of θ, but always respecting the limits of the threshold.

Figure 4.9 shows an example of the update of θ depending on the values of $d(a^h, a^r)$ throughout 5 consecutive poses. For clarity, in this example there is only one try per pose. The first pose is correct since less than 20% of the calculated distances are over the threshold. However, it is not decreased because its value is the minimum. The second one is incorrect, so the threshold is increased by 4% for the next pose. The third pose would have been incorrect if the threshold had not been increased. This and the last two poses are correct so the threshold is decreased by 2% each one until reaching the minimum again.

The capabilities of patients can differ widely, so it is necessary to customize the level of difficulty while training for rehabilitation purposes. This explains how the system behaves by being more permissive or not according to the performance and success of the patient during the session. The pose comparison values and threshold are also used to change the color of the eyes of the robot from red to green according to the correctness of the pose. The limits of θ were estimated during evaluation sessions in which therapists labeled several postures as correct or incorrect to determine the average values of the minimum and the maximum. In the same way, the update

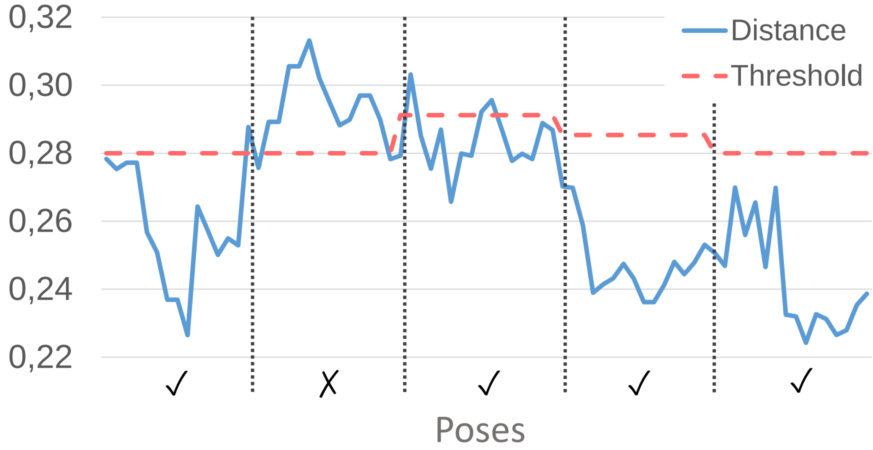


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Figure 4.9: Example of the evolution of the dynamic-comparison threshold according to the calculated distance $d(a^h, a^r)$ for each processed video frame throughout 5 consecutive poses.

percentages of θ were established experimentally by the therapists to find a suitable speed of the evolution of the threshold for the targeted patients. Although currently the same values are used for every patient, it is planned to have a customized set of constants in a future work.

The comparison made for each received video frame throughout the duration of the pose and the use of the dynamic threshold allow both the patient and 3D sensor to have enough margin of failures and inaccuracies without compromising a fluent interaction. We assume that the majority of the detection errors can be absorbed by this battery of consecutive comparisons.

Situation awareness refers to those situations that can appear during sessions and are taken into account in our model. All situations considered can be included in the deliberative model using the Vision component to act accordingly. For instance, if the patient leaves the training area, sits down or stops doing the exercises.

4.7.2 Feedback Mechanisms

When comparing the pose, the Vision component gives an array of numbers to the Executive which indicates how much the patient has deviated from the expected pose. Based on these numbers, the dynamic-comparison threshold value and the current attempt, the Executive component starts the correction mechanism (Figure 4.10).

Algorithm 2: Execute Pose.

```
Input: Pose, Duration
Data: Threshold
Output: Execution result
Failures ← 0;
Accepted ← False;
while Failures < 3 and not Accepted do
    RobotBehavior(Pose);
    Check ← CheckPose(Pose, Duration, Threshold);
    if Check = PatientNotReady then
        RobotBehavior(PatientNotReady);
    else if Check = PoseOk then
        RobotBehavior(PoseOk);
        UpdateThreshold(Failures);
        Accepted ← True;
    else if Failures = 0 then
        Failures ← 1;
        RobotBehavior(NormalCorrect(Pose, Check));
    else if Failures = 1 then
        Failures ← 2;
        RobotBehavior(MirrorCorrect(Pose, Check));
    else
        Failures ← 3;
        RobotBehavior(PoseSkipped);
        UpdateThreshold(Failures);
    end
end
return Accepted;
```

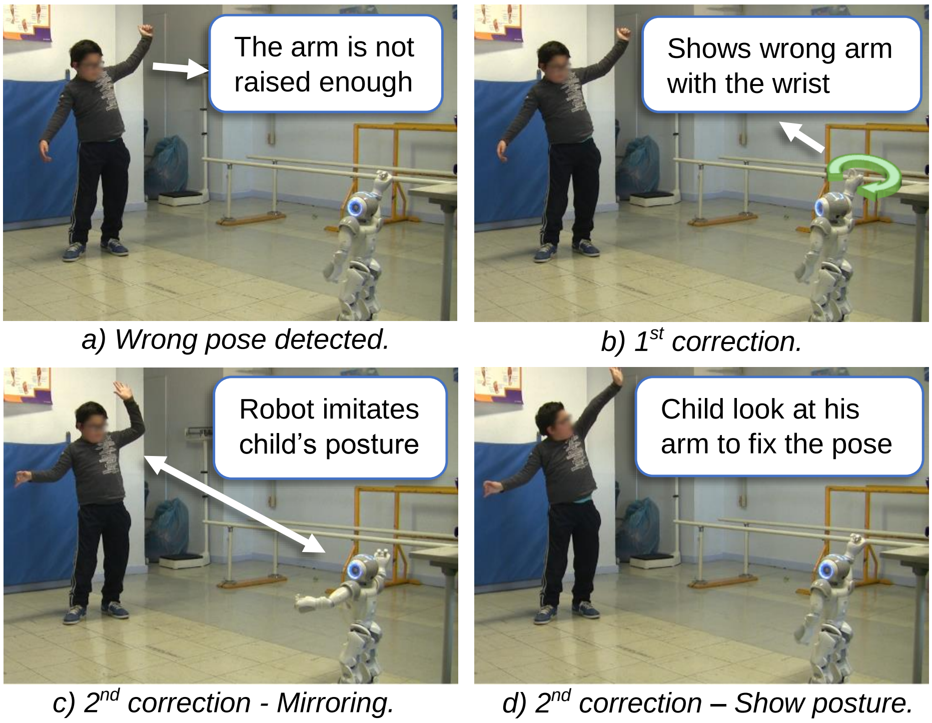

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Figure 4.10: Pose-correction procedure: first correction (standard) and second correction (mirrored).

In the first correction, the robot twists the wrist of the incorrect arm or arms and tells the child that the pose must be corrected. In the second correction, the robot imitates the detected posture of the patient, approximately, and shows him how to move the arms to achieve the correct pose. This is called "mirrored correction". Algorithm 2 describes when to carry out each correction. These two mechanisms provide helpful feedback to users and help them to get closer to the correct pose. If the patient fails these two corrections, the pose is omitted.

4.7.3 Reward System

Regarding the positive reinforcement given by the robot, Naotherapist integrates a reward system adapted to the patient's performance during the exercise execution. This reward system includes a great variety of animations. Likewise, due to the possible heterogeneity of the patients, we have also included new mechanisms of adaptation considering the progress made by the patient to determine the difficulty of the exercises.

The policy used is "the more effort, the better the reward". The system has stored robot behaviors such as dances, songs, choreographies, animations and storytelling, that the NAO robot can execute very spectacularly. The system offers the best rewards when the patient finishes the exercise with few attempts, that is, s/he has needed few corrections during the exercise. However, this policy is not always fixed, since a random multiplier could surprise the patient at any time.

4.8 Graphical User Interface

Figure 4.11 shows the NAOTherapist configuration interface with which the therapists can configure each of the patient sessions. This interface translates the configuration parameters and the selected activities into an automatic planning problem in PDDL. In this way, the engineer is removed from the configuration task and therapists are able to deploy, configure and execute the platform by themselves.

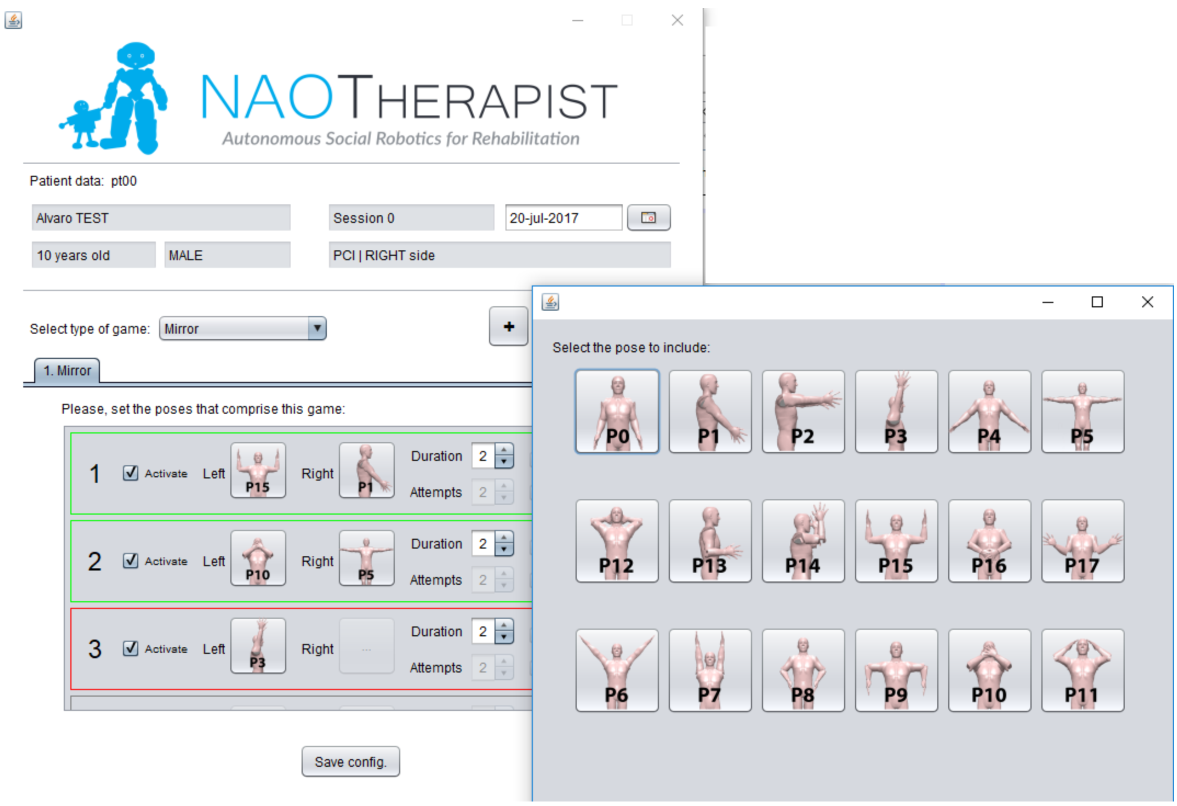

Figure 4.11: NAOTherapist Configuration Interface.

Chapter 5

Evaluation of NAOTherapist

This thesis aims to validate the hands-off cHRI framework in clinical settings presented in Chapter 3. For this, a first prototype, called NAOTherapist, was implemented based on this rehabilitation framework, explained before in Chapter 4. This new chapter contributes with one of the most extensive evaluations in current literature of SAR. First, the chronology is presented in Section 5.1. Next, it extends explaining each of the three evaluation episodes: 1. the first contact, involving 117 typically developing children and 3 patients in a single session (Section 5.2); 2. the long-term adherence, where 8 patients received robotic rehabilitation in a 4-month study (Section 5.3); and 3. the intensive therapy, the most demanding scenario providing 10 patients with daily gamified SAR-based sessions (Section 5.4).

5.1 Chronology

This section explains the chronologically ordered evaluation strategy that was carried out in NAOTherapist. Figure 5.1 shows the characteristics of each evaluation and the evolution of the state of the system in each phase. The platform was involved in three different evaluation episodes: first contact, long-term adherence and intensive therapy. The first contact phase was held from October 2014 to February 2015. During this period, 117 typically developing children interacted with the earliest prototype in an only session [Pulido et al. 2017]. This version of the system was an early prototype with a use case based on the Mirror game. The platform at that moment was equipped with RGB-D sensor and was able to react autonomously. The main objective was to assess the cHRI provided by the platform. In the same phase, a pilot study was conducted with 3 patients for collecting feedback and new improvement requirements.

In the second episode, the platform was deployed in the Virgen del Rocío University Hospital for a long-term adherence study [Pulido et al. 2019]. For 4 months (November 2015 to March 2016), 9 patients with OBPP and ICP had weekly rehabilitation sessions, the first two months with traditional therapy and the second two with NAOTherapist. At this moment, the platform presented some improvements with respect to the initial phase: the Memory game was included, the patients received a fixed reward after each exercise, the patients made individualized sessions and the system incorporated a basic adaptation mechanism when correcting a pose.

In the last episode, the platform participated in an intensive therapy camp with 10 patients with daily sessions for 11 days. This summer camp was held in July-August 2017 at the European University of Madrid with cerebral palsy patients from the DACER foundation. The system was highly improved since it would be evaluated in an environment of maximum demand [Estévez et al. 2017]. Patients had to be daily engaged with the robot. Game mechanics were included as narrative immersion and new game-like activities. The adaptation mechanism was improved by making it more specific about the affected part of the patient. A configuration interface was developed and the rewards catalog was expanded.

			First Contact		Long term adherence	Intensive therapy
			1st Phase	2nd Phase	3rd Phase	4th Phase
			Oct 2014 – Feb 2015	Feb 2015	Nov 2015 - March 2016	July 2017
Characteristics	Evaluation	Clinical settings	✗	✓	✓	✓
		Participants	117	3	8	10
		Condition	TD	OBPP/CP	OBPP/CP	CP
		Sessions	1	1	12	11
		Frequency	-	-	weekly	daily
	System	Autonomy	✓	✓	✓	✓
		Perception	✓	✓	✓	✓
		Adaptation	✗	✗	✓	✓
		Configuration	✗	✗	✗	✓
		Gamification	✗	✗	✗	✓
		Reward	✗	✗	✓	✓
	SAR-based Activities	Mirror	✓	✓	✓	✓
		Memory	✗	✗	✓	✓
		NAO says	✗	✗	✗	✓
		Dance w NAO	✗	✗	✗	✓
		Teach me	✗	✗	✗	✓

Table 5.1: Chronology of Evaluation.

5.2 Episode 1: First Contact

In pediatric rehabilitation, patients are children who need constant motivational reinforcement from the therapists and a great variety of activities. Our robotic platform focuses on upper-limb motor rehabilitation for patients that suffer from cerebral palsy and obstetric brachial plexus palsy. The biggest challenge is to ensure that the patients are committed and follow the prescribed treatment closely. So, proving that the NAOTherapist platform is able to achieve an active engagement with patients in pediatric rehabilitation is required.

5.2.1 Objectives

Two different scenarios and users have been selected: on the one hand, a large number of healthy children in schools to determine the degree of engagement in the activity together with the autonomy of the robotic system. On the other hand, three selected pediatric patients from the Virgen del Rocío University Hospital (VRUH) of Seville have a first experience with the robotic tool and share their impression of the usefulness of the NAOTherapist prototype. The evaluation mechanisms are based on questionnaires to participants, relatives and experts, interaction level from video analysis and logs of the vision-action system. The results of this evaluation seek to demonstrate the potential of these novel robotic tools in the area of pediatric rehabilitation, where a social robot is an extra motivational component to facilitate the development of these tedious treatments.

5.2.2 Experimental Design

Two main types of evaluation were carried out: the first type was carried out with 117 healthy children from two schools. All participants were volunteers that speak Spanish as their first language with ages between 5 and 9 years old (see Table 5.3). NAOTherapist was presented as an educational activity about robotics in the school. The main objective of this evaluation was to analyze the child-robot interaction and solve incoming technical issues. The architecture was improved after each experiment to prepare a polished version for the second type of evaluation that was made in the HUVR with 3 patients with upper-limb motor impairments. The main objectives were to evaluate the performance of the overall architecture in a real-case scenario and the children's reactions using NAOTherapist as a rehabilitation support tool.

These are not long-term experiments, but they allow our objectives to be evaluated at this development stage: the autonomy of the robotic platform, the quality of the child-robot interaction, and the ability of the robotic framework to engage the children throughout the therapy. All data was extracted using application logs, questionnaires, video annotations and the observers' comments.

5.2.2.1 Procedure Design

All evaluations in schools share the same setup (Figure 5.1). Before interacting with the robot, the participants had a first contact with NAO. They can see its appearance, features and some basic skills, but the child does not know exactly how the therapy session works. Then, the child is accompanied to the experimental room and he waits in front of the robot, until the activity starts.

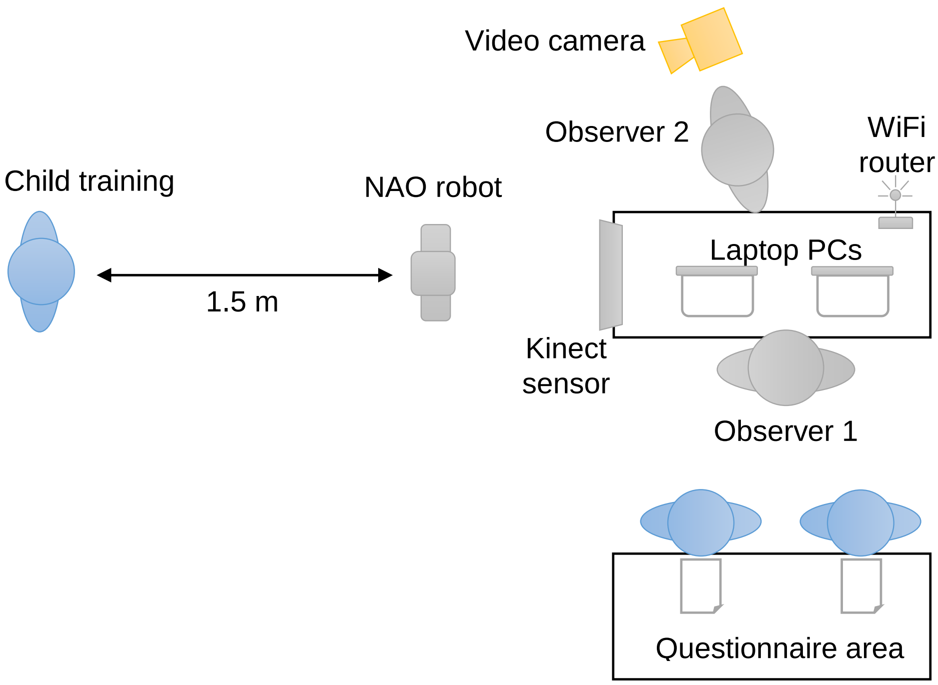

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Figure 5.1: Experimental setup for the schoolchildren evaluations.

The use case starts when the child enters in the experimental room and finds the robot seated and "sleeping" at around 1.5 meters from him. Then, the system carries out the appropriate actions one by one to establish the session. NAO starts blinking and wakes up greeting the child and explains how they are going to do exercises together with the arms. Then, they train using the different exercises in the evaluation: 2 for schoolchildren and 4 for pediatric patients. When the training finishes, the robot wipes sweat from his brow, congratulates the child, says good-bye and goes to sleep again. Finally, the children fill a questionnaire whose results are detailed later in Section 5.2.3.1. The session is closely observed by two researchers without interfering in the process since it works autonomously until the end. The children could ask any question to the observers in order to answer the questions as correctly as possible.

Robotic rehabilitation therapy sessions involve several problems which are addressed by the NAOTherapist architecture such as RGBD human pose detection, inverse kinematics and task planning and replanning. In the evaluation, the exercises come from real activities used in the hospital to rehabilitate children with these disabilities. The poses showed by the robot have been designed by the clinical experts taking into account these two criteria: the poses should be detectable by the RGB-D sensor and should be also executable by the NAO robot. This means that our system has two limitations that every professional must consider, the first is because of the detectable poses of the RGB-D sensor and the second because of the pose compatibility with the joints of the NAO robot.

5.2.2.2 Hypotheses

The experiments of these evaluations aim to validate the following hypotheses:

- **H1**. "Children are engaged with the therapy and make an effort to follow the session with the robot".
- **H2**. "Children like to do the exercises with the robot".
- **H3**. "Children consider the robot as a social and friendly entity".
- **H4**. "Children are able to carry out the rehabilitation session without previous explanations".
- **H5**. "The robot is able to carry out the session autonomously and fluently".
- **H6**. "Experts of the hospital consider that the robot is a useful clinical support tool for rehabilitation".

5.2.2.3 Measurements and Metrics

In order to validate the proposed hypotheses, three evaluation mechanisms are used: questionnaires, analysis of the video data and application logs.

The questions in the questionnaires have only two or three possible options. This was recommended by the therapists consulted because it is clearer for young children to have few options to reply. Statements of the children's questionnaire are included in Appendix B.1. In the following, almost all of the results of the questionnaires are presented with a value of between 0 and 1, being 1 the most desirable option for us. For the evaluation in the hospital, a questionnaire for the observers (family, physicians and therapists) is provided. The questions are detailed in Appendix B.2.

In the children's questionnaire, they also have to select five adjectives from a list which they think are better to describe the robot. These adjectives are classified to measure their perception of the robot as a social entity, instead of an artificial one. Social adjectives like friendly or angry increase the score (+2 for good ones or +1 for bad) and other adjectives for artificial entities like artificial or delicate decrease the score (-1 for good ones or -2 for bad). There is a balanced list of 8 social and 8 artificial adjectives. The social vs. artificial perception metric can take values from -9 to 9.

The sessions of the last 50 schoolchildren share the same set of exercises, forming a very homogeneous group to analyze their video data. Annotations with continuous duration values were used in accordance to Table 5.2. The quantitative evaluation of these annotations allows the reactions of the child to be classified on four different aspects of interaction: emotions during the session, effort and attitude while performing the activities, the child's gaze and the communication with the robot. Each aspect has a track of annotations indicating the corresponding behavior at every moment.

The interaction level is different throughout the session, so it was convenient to divide the sessions into 6 logical segments to analyze the child's reactions separately. Using continuous data from the video annotations, the Interaction Level (IL) metric is calculated to determine the quality of the interaction for each segment. To obtain the IL, the average duration for each behavior of each annotation track is calculated and then, these duration values are normalized by dividing them by the average of the total duration of the segment. Next, the values calculated for each behavior are multiplied by the corresponding score shown in Table 5.2. Finally, all behavior values are added together for every aspect of interaction (Emotions, Gaze, Communication and Attitude) and apply Equation 5.1, which is an adaptation of Fridin's formula [Fridin 2014] to use

Aspect	Score	Behavior
Emotions	2	Enjoyment, happiness
	1	Engagement, focus
	0	Neutral
	-1	Anxiety, frustration
	-2	Boredom, laziness
	-3	Fear, displeasure
Attitude	1	Enthusiastic, energetic
	0	Proper
	-1	Lazy
	-2	Do not train
Gaze	1	Look at the robot
	0	Look at himself
	-1	Look at others
	-2	Not involved
Communication	2	Speak and gestures
	1	Speak or gestures
	0	Hear the robot
	-1	Speak to others

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Table 5.2: Coding Scheme for Video Annotation.

continuous duration values. Communication and attitude are more relevant than the other aspects in achieving a successful interaction, so their contribution to the final IL value is doubled. In our case, the minimum value is -11 and the maximum is +9. These calculations were done for each segment and for the whole session, considering it as a unique segment.

$$IL = Emotions + Gaze + 2(Commun. + Attitude) \tag{5.1}$$

Each pose is evaluated with an adaptation of the performance metric proposed by Fridin [Fridin 2014]. Its value is 3 if the children carry out the movement correctly at the first attempt, 2 at the second attempt, 1 at the third attempt and 0 if he cannot carry out the pose at all.

5.2.3 Evaluation of the cHRI

NAOTherapist has been evaluated using more than one hundred healthy children in schools using short therapy sessions and with three real patients using full-length sessions. A large number of questionnaires and video data were used to evaluate the child-robot interaction with the developed architecture. For this evaluation, the robotic platform follows the use case for every participant.

Table 5.3 shows the average features of the executed sessions for the 117 healthy children from two schools and 3 pediatric patients. These results include different average calculations of the sessions evaluated: the duration of sessions, the number of planning actions executed by the robot (including exogenous events to finish the session) and percentage of possible attempts made, corrections and skipped or omitted poses. When calculating these results, attempts are considered since the first execution of the pose until the last required correction. This means that a participant always has at least one attempt. Corrections depend on the success of the poses made. So the minimum number of attempts is the number of poses in the session (1 each) and the maximum is the product of the number of poses from the three possible attempts.

As can be seen in Table 5.3, the sessions at the hospital comprise a higher number of poses than at the school. Furthermore, the patients used the 61% of the possible attempts, opposed to the healthy children who only needed 24%.

5.2.3.1 Questionnaires

Table 5.3 also shows the results of the questionnaires. A result below 0.5 is undesirable, but answers below 0.7 are highlighted to clarify those that have the worst results. Questions were coded from Q1 to Q19b. The results of Q9, Q16 and Q17 are just informative.

Almost all schoolchildren decided that it was easy to understand what they had to do with the robot (Q1). There are many differences between the children when they had to decide if the robot was alive or not (Q2). All the children felt that the robot was gazing at them (Q3) but they were not overwhelmed by it (Q4). There are more differences when they have to evaluate whether the robot spoke too much (Q5). According to the observations, some children wanted to have a physical interaction with the robot, or that they were tired of hearing corrections when they were repeatedly doing the exercises wrong.

	Schools	Hospital		
Participants	117	A	B	C
Condition	Healthy	OBPP	OBPP	CP
Age	7.90 ± 1.4	7	9	7
Gender (0=M, 1=F)	0.45	0	0	0
Duration (s)	296 ± 50	772	912	831
Num. actions	65.82 ± 4.6	140	148	146
Min-Max attempts	21.7 – 65.2	44 – 132		
Needed attemp. (%)	24.18 ± 6.7	57.6	63.6	62.1
Corrections (%)	16.12 ± 6.8	36.4	45.5	43.2
Failed poses (%)	9.65 ± 7.0	22.7	31.8	27.3
Q1	0.87 ± 0.3	1	1	1
Q2	0.58 ± 0.5	0	0	0
Q3	0.88 ± 0.2	1	1	1
Q4	0.91 ± 0.3	1	0	1
Q5	0.68 ± 0.5	0	0	0
Q6	0.67 ± 0.3	0.5	0	0
Q9	6.86 ± 4.3	0	10	6
Q10	0.98 ± 0.1	1	0	1
Q11	0.94 ± 0.2	1	0.5	1
Q12	0.87 ± 0.3	1	1	1
Q13a	0.95 ± 0.2	1	1	1
Q13b	0.84 ± 0.3	0	1	1
Q13c	0.97 ± 0.1	1	1	1
Q13d	1.00 ± 0.0	1	1	1
Q15	0.39 ± 0.5	–		
Q16	0.48 ± 0.5	–		
Q17	0.74 ± 0.4	–		
Q18a	0.92 ± 0.2	1	1	1
Q18b	0.81 ± 0.4	1	0	1
Q18c	0.88 ± 0.3	1	1	1
Q19a	0.95 ± 0.1	1	1	1

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Table 5.3: Features and Questionnaires of the Evaluations.

The question about whether the robot had feelings or not (Q6) has similar results to Q2. When the children had to guess the age of the robot (Q9), it was observed that they thought that the robot was a little younger than them. Almost all the schoolchildren agreed that they wanted to have the robot at home (Q10) and even to be attended by it in the hospital (Q11). Q11 has the opposite result than in the previous work of Therapist [Calderita et al. 2014b]. This may be because the NAO robot is smaller than the children, which could make it less intimidating and friendlier than the Ursus robot used in the Therapist project. Furthermore, children did not think that they were scolded by the robot (Q12). They thought that the robot could see them (Q13a) and, surprisingly, also hear them (Q13b), although our system does not have audio recognition capabilities yet. All participants thought that the robot enjoyed playing with them (Q13c) and, if they had to do physiotherapy in hospital, they would rather do it with the robot (Q13d).

The question about whether the robot was correcting a pose which indeed was correct (Q15), had an undesirable result, although the children had problems understanding this question. The system rarely fails when correcting poses, but many children could not understand that they had to put their arms in exactly the same position as the robot showed them. Moreover, even with the eyes changing dynamically from red to green according to the correctness of the pose, some children found it difficult to coordinate their own arms when making the exact pose. The lack of a mirror in front of the participant makes this task difficult, but coordination in this imitation activity is important for the success of the physiotherapy.

Both exercises looked the same (Q16) and the second one was considered more difficult (Q17), as was intended. They also consider that the descriptions of the exercises were easy to understand (Q18a) and the session was not exhausting (Q18b). The feedback with the lights of the eyes was useful (Q18c). Finally, children do not think that the session was boring (Q19a).

Participants also had to select about 5 adjectives from a list of 16 (Q7), as in the previous work of Therapist [Calderita et al. 2014b]. Figure 5.2 presents the list of all adjectives with the proportion of the selected ones. Clearly, all adjectives with a positive connotation have been selected in the first place, which is evidence of the children's acceptance of the system (hypothesis H2). Some of these adjectives like "easy" are used for artificial entities instead of social ones. Each adjective has a positive or negative value according to its connotation and application to a social entity as explained in Section 5.2.2.3. The social vs. artificial metric is calculated by adding all these values together for each child. The average of this metric for each child is 2.475, which indicates that the robot was mostly considered as a social entity validating hypothesis H3.

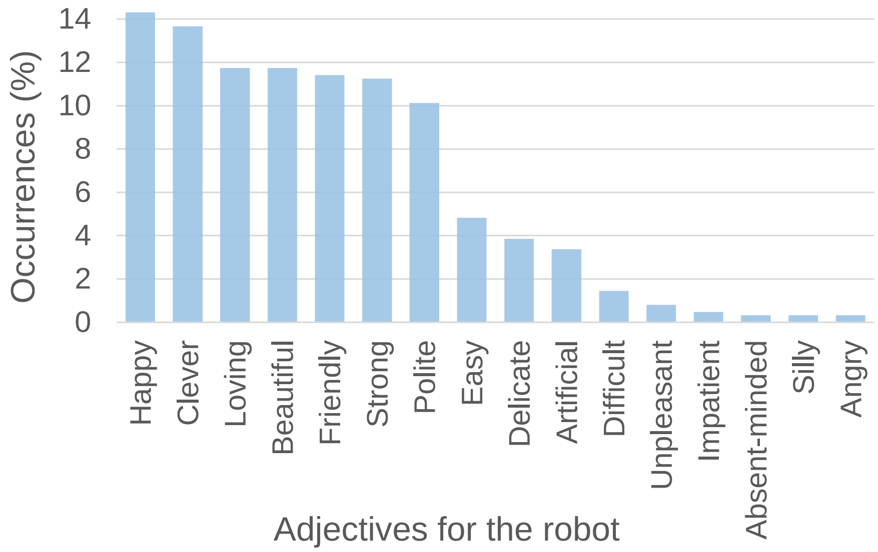

Figure 5.2: Proportion of adjectives selected by the children to describe the robot (Q7).

The children also had to give the robot a name (Q8). This question is difficult to evaluate, but teachers and family confirmed that they often tend to put their own name, a friend's or their pet's name. Older children were more creative with fictitious names. They also were asked for more games they would like to play with the robot (Q14). The majority of them involved physical activities like playing with a ball, running, etc. This suggests that children love to see the robot moving by itself. The final question was free; about whether they liked playing with the robot or not (Q19b). The majority said that they had a lot of fun with the robot because of the way it moves and speaks. Some of them said that they would like to see the robot walking, moving its legs and to be closer to touch it. This question was useful to see the children's expectations for future improvements in the system.

In conclusion, it can be confirmed that schoolchildren did not have any problem following the sessions. They mostly considered the robot as a social entity, although not necessarily alive. The results of the questionnaire show a huge acceptation of the robotic system in all evaluations, as a playmate and as a tool to support their physical rehabilitation. These results are consistent with hypotheses H2 and H3.

5.2.3.2 Video Data Analysis

An in-depth analysis of the last 50 schoolchildren videos were carried out, because they shared the same set of poses and were very comparable between them. The duration of the session is divided into 6 logical segments, containing different activities. In the first-contact segment, the robot wakes up, says "hello" and introduces itself. Then, in the introduction, the robot explains the task that they are going to do to the child. Then, they do a warm-up exercise and a dissociation exercise. Finally, the robot says "good-bye" and, in the parting segment, it sits down and goes to sleep again. Almost the 80% of the time of the session is spent doing exercises and the rest is social interaction with the robot. Our metrics on the video data are based on continuous time values, so it is important to consider each segment of the session individually to extract conclusions from the analysis. All of these metrics were explained in Section 5.2.2.3.

Table 5.4 summarizes the results of the analysis of the annotations for each segment and the full session considered as an individual segment. 5 different types of annotation, or aspects, are shown in this table (E: Emotions, A: Attitude, G: Gaze, C: Communication). The sum of the percentages is 100% for each behavior and each segment. In general, the standard deviations are high, but several conclusions can be drafted in some segments and behaviors. The parting segment has the worst results because children often do not wait for the robot until it is fully seated. They did this to avoid delaying the next participant and start the questionnaire quickly. Annotations on emotions show that most of the time the child is just focused on performing doing the exercises correctly. Children spend more time enjoying segments which are not exercises because they require social interaction. Displeasure values are produced mostly in parting because sometimes children left the robot before it finished the sitting down animation. In the annotation of attitude, the majority of the time the children are well behaved. This is followed by the enthusiastic behavior, corresponding to very motivated children. Almost none of children were apathetic with the robot and during the training session all of them followed the instructions completely. These results are consistent with hypotheses H1, H2 and H3.

Almost all the time children were gazing at the robot. Children rarely look themselves to check their posture and, more frequently, they look away to the observers or other children in the experimental room looking for some kind of feedback. Children usually respond verbally (sometimes shyly) to the robot when it says "hello", "good-bye" and asks how they are. These communications are short but very valuable because they imply an active social interaction (hypothesis H3).

Behavior (%)	First contact	Introduction	Warm-up	Dissociation	Good bye	Parting	Full session
E - Enjoyment	44.09	28.48	7.94	13.70	30.72	26.42	16.31 ± 19.3
E - Engagement	39.24	60.48	84.59	72.11	62.37	46.29	71.48 ± 26.1
E - Neutral	15.35	11.04	6.87	11.94	4.69	24.18	10.60 ± 18.5
E - Frustration	0.00	0.00	0.60	1.83	0.00	0.00	1.03 ± 2.4
E - Boredom	0.00	0.00	0.00	0.42	0.59	1.21	0.29 ± 1.4
E - Displeasure	1.31	0.00	0.00	0.00	1.64	1.90	0.28 ± 1.4
A - Enthusiastic	19.69	23.04	21.52	19.89	20.52	19.34	20.56 ± 30.9
A - Proper	79.00	72.96	74.51	79.00	75.62	64.42	76.38 ± 34.6
A - Lazy	0.00	4.48	4.23	2.26	2.23	2.25	2.84 ± 9.1
A - Do not play	1.57	0.00	0.00	0.00	0.00	14.51	0.78 ± 1.2
G - Look robot	87.40	91.36	92.58	93.00	88.04	76.86	91.34 ± 17.6
G - Look himself	0.00	0.00	0.99	1.45	0.00	0.00	0.97 ± 1.8
G - Look others	11.15	8.16	6.32	6.26	13.48	10.71	7.39 ± 9.3
G - Distracted	1.05	0.00	0.00	0.00	0.00	12.78	0.67 ± 1.1
C - Voice + gestures	14.57	8.48	1.65	3.54	12.31	13.82	4.98 ± 9.0
C - Voice / gestures	8.40	12.32	0.44	0.95	7.15	7.43	2.56 ± 2.4
C - Hear robot	72.05	78.08	97.73	95.05	81.36	63.04	91.14 ± 21.0
C - Speak others	4.07	0.32	0.57	1.25	0.23	15.72	1.78 ± 2.5

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Table 5.4: Behavior Distribution throughout the Segments of a Session.

A graphical view of the interaction is shown in Figure 5.3. This figure shows the interaction level metric for each segment and the contribution for each aspect of interaction. Higher levels of interaction are reached in segments in which there are no exercises, because these segments are only based on social interaction. Emotions and communication are clearly lower in segments with exercises because focusing on training is enough to do them correctly. Attitude and gaze are the same in all segments (except in parting) as the child is almost always looking at the robot to follow its instructions. In parting, attitude has a negative contribution because children do not wait until the robot is fully seated. All segments show an active engagement of the children. This is consistent with hypotheses H1, H2 and H3.

In these experiments, the postures of the arms are intended to be imitated easily by healthy children. Moreover, testing a hard, unnatural posture for them is wanted to give rise to a lot of corrections. This posture requires the elbow to be maintained at the shoulder height and the hand down at an angle of 90 degrees to the elbow joint. This is identified with a 7 in our system (inverse flexion), as shown in Figure 5.4. The resting posture has the identifier 0 and it is not considered when comparing the pose. Postures 8 and 9 and postures 1 and 3 differ only in wrist rotations. These differences cannot be detected accurately with the skeleton-tracking algorithm of RGB-D sensor, so they are compared as the same pose.

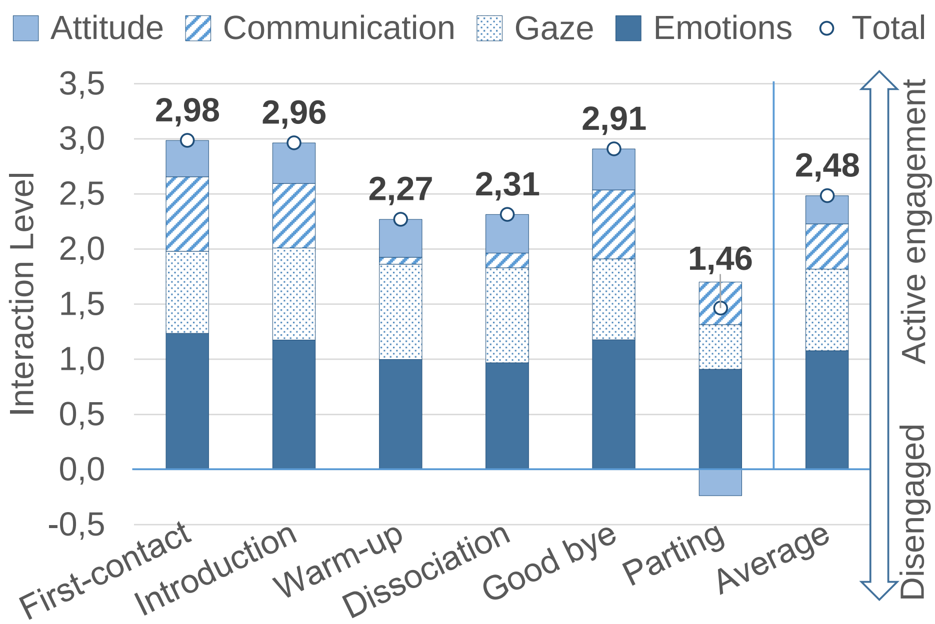

Figure 5.3: Average Interaction Level (IL) distribution throughout the segments of the session.

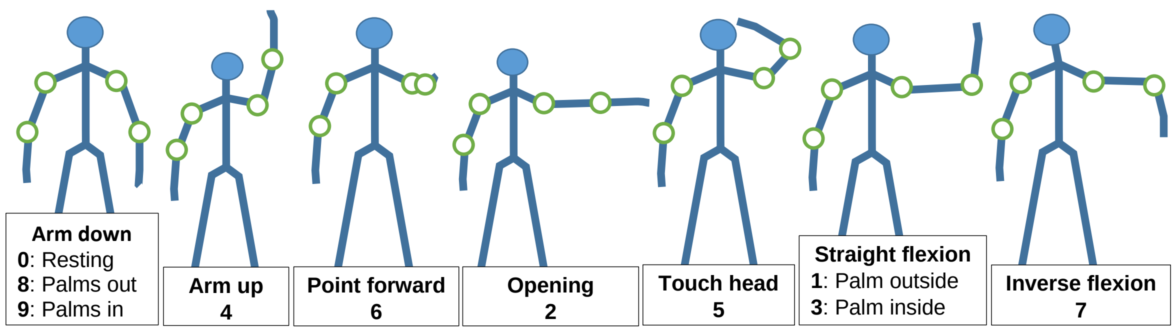

Figure 5.4: Frontal diagrams and numeric identifiers for each tested posture in our system. In this figure, the right arm has always the posture 0.

Figure 5.5 shows a bar for every pose in the sessions together with the average value of the performance metric. The name of the pose contains the code of the posture for each arm. Poses with the posture 7 (the unnatural one) have low performance, as expected. Postures 8 and 9 only require the arms to be down with different wrist angles, so their performance value is high. The last pose (6-6) is simple, but confusing in practice. In this one, both arms must be straight and pointing out in front. The children usually believed that they had to point at the robot with their arms, lowering them too much because the NAO robot is shorter than them. Sometimes this pose is well done, but the Vision component has problems in comparing the angles of the joints because the arms are perpendicular to the plane of the RGB-D sensor.

The first poses of the session contain posture 4, which requires the arms to be straight and up. In these first poses, the children tend to raise their arms shyly, with their hands at the height of the head. Similar problems are found in posture 3 (the same as in 7, but with the hands up). After the first corrections, the children get the clue from the color of the eyes and they know how to do the exercises much better for the following poses (hypothesis H4). Small detection problems were observed in posture 4 when children have thin complexion, wearing a scarf or have long hair in front of their shoulders. In all cases the session was able to continue normally. The children smile with posture 5, which requires a hand on top of the head.

The results of the analysis of the video annotations are coherent with the observers' comments and the questionnaires. The children were focused on the activity, they enjoyed the session trying to do the exercises as well as possible and they interacted socially with the robot. The robot is able to do the full session autonomously with no problems. Therefore, video data support hypotheses H1 to H5.

5.2.4 Evaluation with Pediatric Patients

The last evaluation was carried out with 3 males[1], two seven year-olds and one nine year-old. They are pediatric patients from the *Hospital Universitario Virgen del Rocío* (HUVR). Two of them have obstetric brachial plexus palsy (OBPP) and the other suffers from cerebral palsy (CP). In some cases, they exhibit some degree of dystonia (twisting and unintentional movements) while performing the exercises. The experimental conditions were very similar to the previous evaluations. 4 exercises were used instead of 2: warming up, maintaining poses, dissociation poses and cooling down. Each child had his own motor disabilities, but the exercises in all of the sessions were the same for experimental purposes. The experimental room chosen was where these children usually do their physiotherapy exercises. However, in this case, there were observers such as physicians, therapists and technicians who, after the session, also filled in a different questionnaire. Next to the training area, there was a window from which the child's family and other observers were able to watch the therapy session.

[1]Online videos of the evaluations in the HUVR:
Patient A: https://youtu.be/9n9nlI28rME
Patient B: https://youtu.be/77a20MzLVwQ
Patient C: https://youtu.be/kV-_b-sd54I

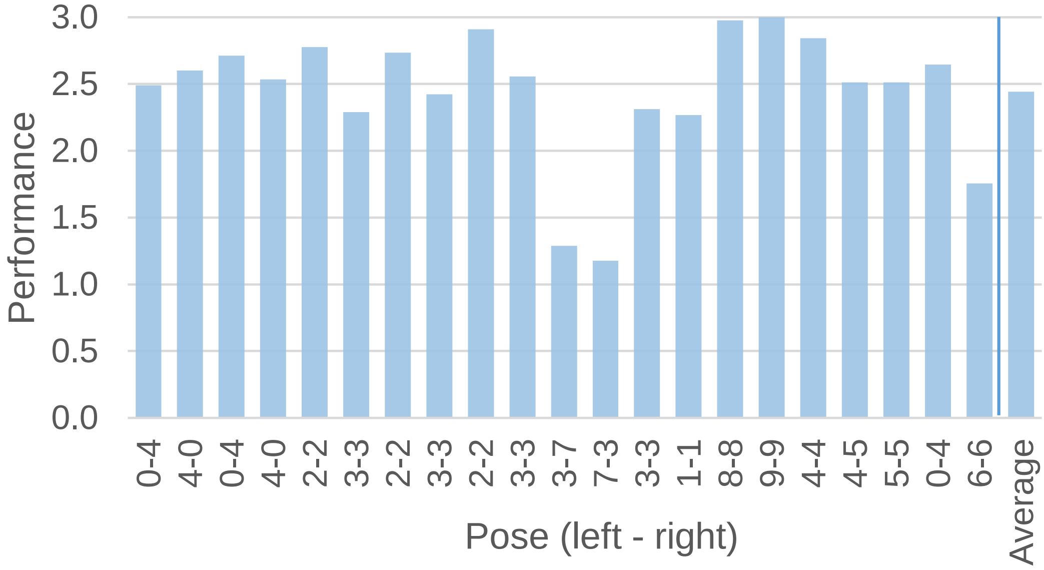

Figure 5.5: Performance measurements for each pose. A 0 means that the child failed to make the pose after three attempts, and a 3 means that the children performed the pose at the first try. Each pose contains the code of the posture for the left and right arm, separated by a hyphen.

The children did the exercises well, in spite of them lasting about 15-20 minutes of rehabilitation, which for them is long. The children were used to do similar rehabilitation movements and they understood the procedure quickly. The dynamic-comparison threshold was more permissive when the child failed several consecutive times. This avoided too many corrections for the same child.

The questionnaires for children (Table 5.3) were the same as those for the school, although the questions had to be explained by adults. Questions which required writing (Q7, Q8, Q14 and Q19b) or evaluating technical aspects of the exercises (Q15, Q16 and Q17) were not answered by all participants, so they were not assessed. The results have several interesting differences from those from the school, although pediatric patients are too few to be representative enough. They thought that the robot was not alive (Q2), but it had “some feelings” (Q6). All of them thought that the robot spoke too much (Q5), probably because it was the first time that the system was tested with full-length sessions and they had to make many corrections, in spite of all of them agreeing that the session was fun and productive (Q19a). The children considered the robot a therapeutic toy because they all agreed to do more physiotherapy sessions with it (Q13d).

There were different duration requirements when designing the sessions for schoolchildren and pediatric patients. The sessions in schools lasted about 5 minutes while in the hospital reached 15 minutes. This difference gave patients more time to realize that the robot was not able to hear them (Q13b) and they found the session more tiring (Q18). The latter could be the reason why one patient would rather not have the robot at home (Q10).

The physicians and the therapists thought that the robot was a very useful tool. A physician detected certain clinical aspects on a participant that she never realized before. The children were uninhibited with the robot and, when repeating and performing movements, some unseen limitations or capacities could have appeared. So the robotic system has proven to be a useful tool for diagnosis too.

After each patient's session, the respective family, two physicians and a therapist filled in a questionnaire whose results are shown in Table 5.5. As a reminder, the answers to the questionnaires are represented from 0 to 1, 1 being the most positive result in our evaluations. All questions obtained very positive results although there are some differences between each group. Both the family and the therapists thought that the children had understood what to do (Q1), but sometimes the physicians did not think so. In general, the movements of the robot are natural (Q2), the children carried out all poses naturally (Q3) and they were not overwhelmed with the session (Q4). For therapists, Q2, Q3 and Q4 did not produced the most desirable answer because, for evaluation purposes, all exercises were the same in all sessions and, consequently, they were not adapted to the child's requirements. All observers agreed on all the following questions: the robot only corrected incorrect poses (Q5), the sessions were carried out by the robot fluently (Q6), the children were engaged in the session (Q7), this was a beneficial experience for them (Q8), the patients made an effort to do the exercises (Q9) and finally that the robot was a useful tool in rehabilitating children with these medical conditions (Q10). These results reinforce hypothesis H6, although to establish the final conclusions, a wider, long-term evaluation with more pediatric patients is required [Leite et al. 2013].

5.2.5 Discussion

The evaluation presented in this work has been carried out with more than 120 children. Our architecture is able to perform all physiotherapy sessions autonomously without the need for human intervention (H5). Although the results of the questionnaires reveal

	Family	Physicians	Therapists	Total
Q1	1.00	0.67	0.83	0.79 ± 0.3
Q2	1.00	1.00	0.50	0.88 ± 0.2
Q3	1.00	0.92	0.67	0.88 ± 0.2
Q4	1.00	0.75	0.42	0.73 ± 0.3
Q5	1.00	1.00	1.00	1.00 ± 0.0
Q6	1.00	1.00	1.00	1.00 ± 0.0
Q7	1.00	0.92	1.00	0.96 ± 0.1
Q8	1.00	1.00	1.00	1.00 ± 0.0
Q9	0.83	0.92	1.00	0.92 ± 0.2
Q10	1.00	1.00	1.00	1.00 ± 0.0

Published in [Pulido et al. 2017]

Table 5.5: Results of the Questionnaires for Observers and Experts.

that not all participants consider that the robot was alive, the behavior, speech and appearance of the robot guarantee its social prominence in spite of the fact that there were always other observers in the room (H3).

According to the results of the interaction, the participants enjoyed themselves while training with the NAO robot (H2) and they have shown themselves to be motivated and engaged (H1). In fact, there were children who had more difficulties achieving certain poses, but they did not give up trying to surpass themselves. In most cases; the children figured out how to train with the robot without any help (H4) and, after few attempts and corrections, they managed to perform the rest of the exercises correctly by themselves. The videos of the pediatric patients show the great effort made by them during the physiotherapy session. When playing with a robot, children become be uninhibited, having an active engagement and being committed to the exercises.

Our experiments involve only one session for each child, always having their first contact with the robot. The results are very promising because children want to repeat the experience, but it would be necessary to carry out long-term experiments to decide whether the children's engagement is maintained over time (H6). Experts have an optimistic attitude in this regard. Few children currently have the opportunity to interact with a social robot like NAO, so the chance to play with it gives an interesting plus to the physiotherapy therapy. The children could find new motivation to continue their treatment by playing with the robot.

The deployment of the NAOTherapist platform is agile and not very expensive, so it seems to be an interesting investment for a hospital or a children's physiotherapy center. Our system may be considered as a novel physiotherapy service assisted by a humanoid robot whose beneficiaries are not only patients but also physicians and therapists, since our system could be a new objective tool for diagnosis.

Moreover, the NAOTherapist architecture is one of the few whose execution of the rehabilitation therapy is carried out autonomously and has already had a warm reception from the children, their family and experts. Its later integration into the Therapist project will allow the incorporation of more functions such as clinical metrics capture, clinical reports generation, facial recognition or voice interaction.

Our new challenges should focus on the capability of the robot to change and maintain their empathy with the patient throughout all of the sessions of his therapy. In this sense, the robot should provide new behaviors and games which the patient may consider attractive to play and maintain or increase adherence to the physiotherapy treatment.

5.3 Episode 2: Long Term Adherence

For children with deficits, or at risk of suffering from them, early stimulation is a fundamental part in the development of the first three years of life, since it allows to enhance physical, cognitive and sensory abilities depending on the affected areas [Majnemer 1998]. In pediatric rehabilitation, one of the main objectives of the early motor stimulation is to optimize the patient's potential by exploiting the concept of neuroplasticity, and compensate for their deficits so that they can improve their quality of life and have a full and satisfying life in the future. To this end, neuro-rehabilitation therapy requires a constant commitment of the patient and their relatives, and adherence to an intensive treatment prolonged over time. To be effective, the patients should start their therapy, as soon as possible, but following a personalized treatment that is adapted to their condition and progression [Mahoney et al. 2004]. Both issues are not always easy to satisfy, given the limited availability of professionals and the lack of time to monitor the progression.

5.3.1 Previous evaluations

NT platform was initially evaluated in two phases [Pulido et al. 2017]: the first phase was carried out with 117 typically developing children to measure the degree of interaction and improve the autonomy of the prototype in accordance with the ongoing requirements. [2] Without any prior explanation, typically developing children were able to follow the session and they mostly considered the robot as a social entity being actively engaged throughout the activity. After that, in a second phase, three pediatric patients from the Virgen del Rocío University Hospital (VRUH) had a first experience with NAO and shared their impression of the usefulness of the NT prototype. [3] They enjoyed the activity and were delighted to participate in future evaluations. In both phases, participants were able to follow the sessions with the instructions from the robot. The robot autonomy is considered as a key point, so making the robot taking its own decisions improves the perception of the social entity which may promote an active engagement of the patient. We ensured that patients feel supported by giving them a set of verbal and visual cues. We also detected the need to create a reward system that would reinforce the patient for every well-done exercise, which would be later a key factor in maintaining patients engaged with the treatment. After

[2] Video of the NAOTherapist use case: https://youtu.be/75xb39Q8QEg
[3] Videos of the 2nd evaluation: https://goo.gl/ZtfrVQ

this previous experience, we took all these elements into account in improving the NT architecture [González et al. 2017].

5.3.2 Objectives

After the initial evaluations, the next step is to expose the developed technology in a long-term experience. This work aims at providing new results of a 4-months evaluation of our socially assistive robotic platform with pediatric patients of the VRUH. The key points to evaluate are: firstly, to demonstrate the feasibility of using the NT robotic platform in a clinical setting during a long-term exposure. Secondly, to remove the presence of the robotic engineer during the execution of the sessions. To do this, the therapist must be trained in the use of the tool, at the same time as the system should be sufficiently robust. Thirdly, to gather the impressions related to the acceptance and satisfaction of technology by both patients and their relatives that will help to improve the system. Additionally, clinical results are also of interest to this work, which will be preliminary, due to the short period of the study and the nature of these pathologies that present a long progression.

5.3.3 Experimental Design

The long-term adherence study lasted from November 2015 to March 2016. The sessions were conducted by a specialized therapist without the need of an engineer there. This section describes the entire experimental process that was carried out for the collection of participant data.

5.3.3.1 Procedure Design

Before carrying out this study, a therapist was trained to deploy and use the platform by himself, every time he scheduled a session with the patients. Based on the clinical guidelines of traditional treatments, a two-step procedure was defined together with the professionals of the VRUH. Figure 5.6 shows this division. The first step refers to the session configuration that was carried out prior to the training, and the second step comprised the execution and the interaction phase.

The therapist was responsible for adapting the exercises of the session to the capabilities and the evolution of each patient. This configuration process also involved

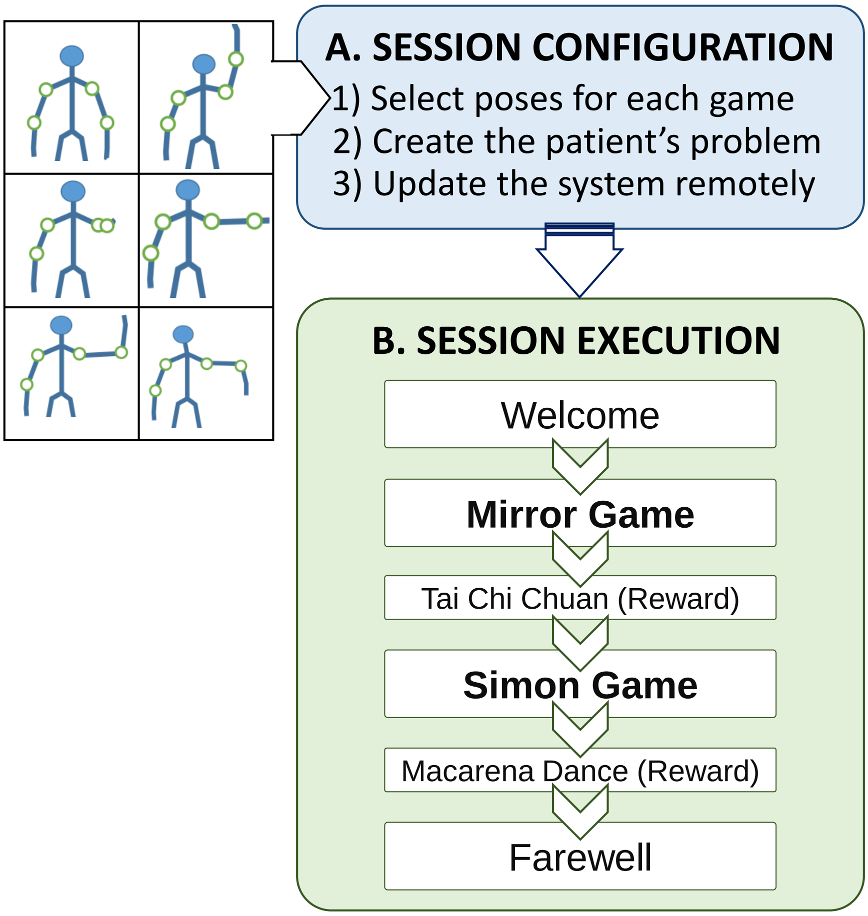

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Figure 5.6: 2-step session procedure: A. configuration and B. execution.

the engineer, who translated these preferences into a PDDL problem that remotely updated the patient's session profile. [4]

The step B involved only the patient and the therapist. Once the session was initiated, the therapist could pause and resume the session using the robot's head buttons. The platform had a database of pre-recorded speech to communicate and coach the patient. All sessions comprised three phases: Welcome, Training and Farewell. In the first phase, the robot gave a personalized greeting and encouraged the patient to start the therapy. Then, the training phase started and the robot introduced both activities. The first activity was the Mirror game followed by the second that was the Simon game, both explained before. Throughout the training, the robot guided the

[4]Current NAOTherapist software includes a Graphical User Interface which permits the therapists to design the sessions by themselves without the support of the engineer.

patients and offered them the necessary verbal and visual cues to help them to correct their posture. The "mirrored correction" was a visual cue that was triggered when the patient's pose was not correct. In this cue, the robot imitated the patient's body showing how their arms should be in accordance with the requested posture [Pulido et al. 2017]. Verbal cues provided clues about which limb was incorrect. Between the exercises, the robot rewarded the patients with a dance or a choreography: "Tai Chi Chuan" and "Macarena Dance" were used in this study. This was an incentive for participants to finish the activities. In the last phase, the robot said goodbye to the patients and invited them to play again the next day.

5.3.3.2 Target subjects

The NT platform is a system specialized in upper limb rehabilitation exercises. This evaluation aims at performing a motor training with pediatric patients affected by OBPP or ICP type hemiparesis. To elaborate a plan of recruitment for the participation of this study, a set of inclusion and exclusion criteria were established that are described as follows.

Inclusion criteria:

- Patients aged 3 - 10 years suffering from OBPP or ICP.
- Recruited or clinically assessed in the Infantile Rehabilitation Service of the VRUH.
- Clinically stable and capable to start the treatment.
- Authorization by their relatives with the corresponding signed agreement.

Exclusion criteria:

- Visual difficulties.
- Pain that makes it impossible to perform exercises.
- Other associated neurological pathologies.

It is important to highlight that since each patient presents different conditions and capacities, it is an indispensable requirement of the platform to offer a customization for each patient of the study. This implies that each session, exercise and group of postures must be adapted and personalized for each subject and modified, if necessary, throughout the study.

5.3.3.3 Experimental setup

All sessions during the study were performed under the same conditions. This section describes the set up of the room and the description of the sessions.

The patients went to all sessions accompanied by their relatives or caregivers. As shown in Figure 5.7, the therapist welcomed them and invited the patient to enter to the training room, while the relatives attended the session from the observation room through a one-way mirror. The patient stood about 1.5 meters from the robot which started "feigning being asleep". The RGB-D sensor was located just behind the robot. The therapist was located next to the laptops to configure and, if necessary, to give indications to the patient. There was also a video camera permanently filming every session.

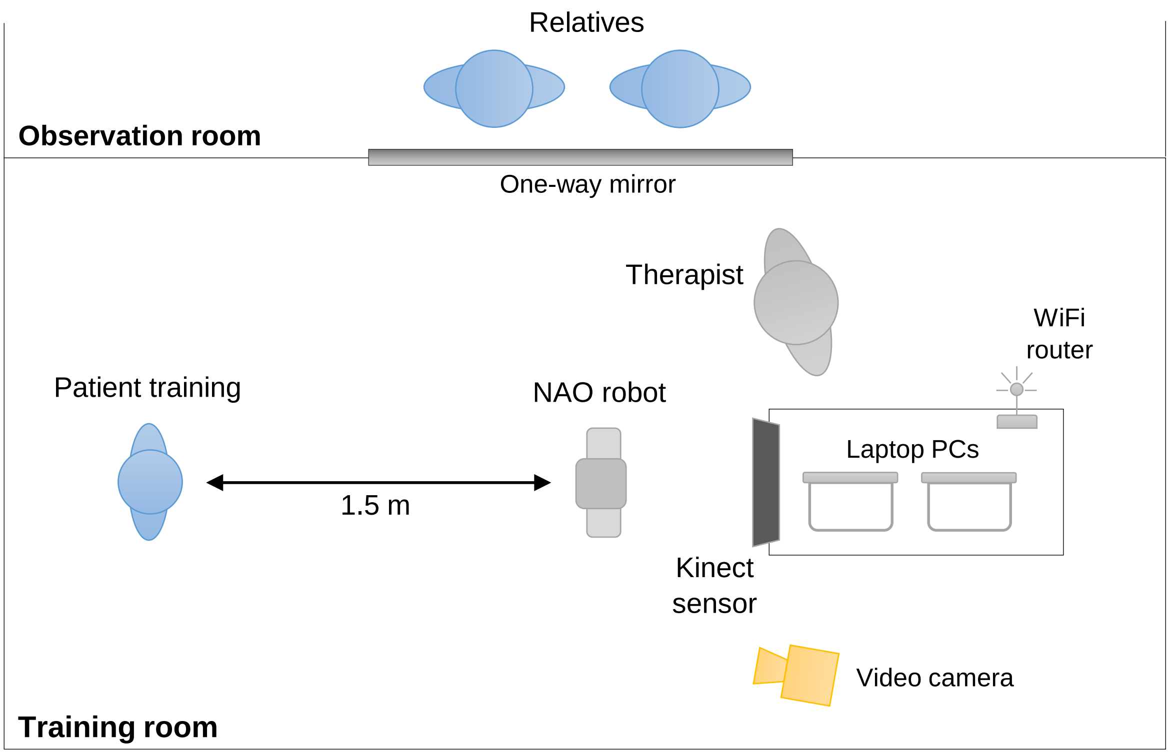

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Figure 5.7: Experimental setup at VRUH.

5.3.3.4 Study Protocol

This section describes the protocol that was carried out during this study. The patients involved in this study were very different among them due to their pathology. Furthermore, patients could do different complementary activities as any child (swimming, dancing, soccer and so on), which may influence in the study. In this sense, the randomized controlled trial was not possible, because the patients could not be recruited and divided in two groups with similar features. Moreover, the recruitment was difficult and the number of the patients was small, so this work proposes a quasi-experimental small N-Design [Graham et al. 2012]. The Small-N design involves serial observations of single individuals or small groups before, during, and after an intervention period. It allows researchers to provide clinicians with practical information for making decisions to improve the care of individual patients. Moreover, it offers a potential avenue for including evaluation and research design in clinical practice and building the foundation for evidence based rehabilitation at the level of the individual patient in actual treatment settings.

Figure 5.8 shows the design of the study and the pre-post evaluation periods that were considered in the assessment.

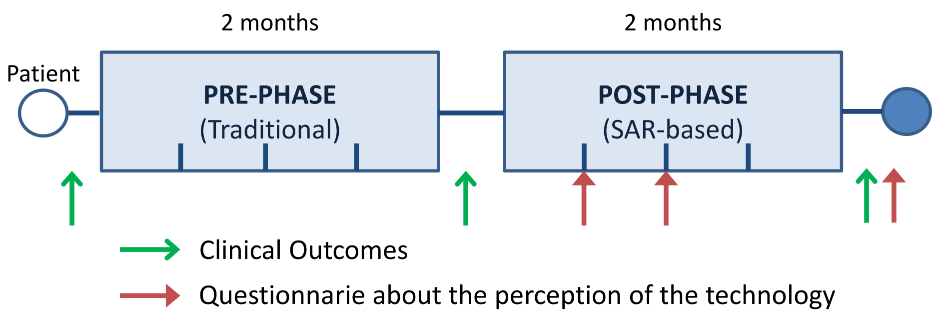

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Figure 5.8: Pre-post evaluation design.

Pre-phase

During this phase, patients followed the traditional motor training that is approved by the VRUH. To that end, the rehabilitation physicians evaluated the patients and defined the objectives according to the patient condition. With these objectives, the physiotherapist designed the personalized training plan consisting of the repetition of motor exercises, stimulating and reinforcing the aspects indicated by the physicians. Rehabilitation sessions were scheduled for patients to visit the hospital twice a week. The duration of the sessions was an average duration of 30 minutes. The training was performed for 2 months. The physicians evaluated the patient at the beginning and at the end of the training.

Table 5.6: Quantitative Items.

Dimension		**Valued item**	**Patient**	**Caregiver/ Relative**	**Clinical experts**
Perceived utility	I.1	Whether the robot is helpful	x	x	x
	I.2	Whether the patient performs the exercises better after using the robot	-	x	x
Easy to use	I.3	Whether the patient is overwhelmed by the robot	x	x	x
	I.4	Whether the exercises are boring	x	x	x
Facilitating conditions	I.5	Whether the platform works correctly	x	x	x
Empathy/	I.6	Whether the patient likes the robot	x	x	x
Social Interaction	I.7	Whether the patient feels motivated to play with the robot again	-	x	-
	I.8	Whether the patient wants to have the robot at home	x	x	-
	I.9	Whether the patient believes that the robot can see him or her	x	-	-

Post-phase

Since the patients in both phases were the same, the final assessment of the pre-phase was considered the initial assessment of the post-phase, as can be seen in Figure 5.8. During this evaluation, the patients performed the motor rehabilitation with the SAR-based robotic platform under the supervision of the physiotherapists. Each session is carried out as follows: The system had a set of personalized motor exercises with the Mirror and Memory activities; and depending on the progression of the patient, the training become automatically harder or more relaxed.

Every session was scheduled for patients to visit the hospital twice a week. The average duration of the sessions was about 30 minutes. The training was performed for two months. The evaluation with the robot was done three times, in the first evaluation of the system (two days after training with the robotic platform), the month of training and at the end (after two months). After that, the physicians assessed the patients for the last time.

5.3.3.5 Study variables

From the objectives of this study, several aspects were addressed. There are input and output variables: First ones correspond to the patient's data and the output variables are related to the clinical assessments, the usability and satisfaction of the technology. The analyzed variables are itemized and separated as follows:

- Input variables:
  - Socio-demographic: age and gender
  - Pathology
- Output variables:
  - Motor function of the upper limb
  - Number and duration of the sessions
  - Usability and satisfaction

5.3.3.6 Measuring instruments

In order to carry out the assessment mentioned above, the following measuring instruments were administered:

1. Motor function:
   - Manual Ability Classification System (MACS) describes how children handle objects in daily activities.
   - Motor scale of MALLET, although this scale is indicated for patients with OBPP, it is also used to assess the overall mobility of the upper limb.
2. Satisfaction and usability:
   - Questionnaires for patients, relatives and clinical staff. Likert-scale (5 items) and open questions.

In relation to the satisfaction and usability questionnaire, three specific questionnaires were designed for patients, relatives and clinical professionals. The questionnaires were designed to address aspects of the quantitative and qualitative dimensions. The quantitative assessment of the survey was designed using the Technology Acceptance Model (TAM) [Venkatesh et al. 2003], which analyzes the dimensions of perceived utility, ease of use, facilitating conditions, and empathy or social interaction. The items that were evaluated in each of the dimensions and for each one of the profiles (patient, caregiver or clinical experts) are indicated in Table 5.6 by an x.

Table 5.7: Qualitative Items.

	Valued question	**Patient**	**Caregiver/ Relative**	**Clinical experts**
Q.1	Would you like to improve the tasks of the robot? Which ones?	x	x	x
Q.2	What is the exercise you like most? (Mirror, Simon, None)	x		
Q.3	What is the most difficult exercise? (Mirror, Simon, None)	x		
Q.4	Have you notice that the patient has improved his capabilities?		x	x
Q.5	Would you like your child to continue participating in the study?		x	
Q.6	Would you like patients to continue with this therapy?			x

To obtain the information of the qualitative dimension, the methodology of semi-structured interview is followed, in which the questions were defined a priori, but some of them were also open formulated. This offered the possibility to the interviewee to provide more nuances. The questions of the qualitative dimension for each profile are indicated in Table 5.7 by an x. As it is represented in Figure 5.8, the questionnaires were provided to patients and relatives three times. The first time was at the beginning of the post-phase, specifically after two days of working with the robot. Then, after one month of training and finally after two months, that is the end of the phase. The professionals completed in the questionnaire at the end of the piloting, that is after finishing the post-phase, in order to make an overall assessment of the system.

5.3.3.7 Hypotheses

The following hypotheses were defined for this study:

- H1. Utility: the system was useful for the purpose it was intended.
- H2. Usability: the platform was easy to deploy and use by the patients and therapists.
- H3. Engagement: the robot was able to keep the patients engaged and motivated during the full period of the study.
- H4. Fluent interaction and robustness: the system was able to guide every session working autonomously and providing a fluent interaction with a high fault tolerance.
- H5. Clinical improvements: clinical assessments registered improvements in patients. Although this hypothesis is of interest to this work, a clinical improvement cannot be attributed to the use of the NAOTherapist platform, since, under the opinion of the experts, it is not feasible to isolate the patients from their daily life activities.

5.3.4 Evaluation Results

In this study, 13 patients were initially recruited from the Infantile Rehabilitation Service of the VRUH as potential candidates, but 5 of them were excluded since they did not either meet the minimum requirements or did not wish to participate in the study. Finally, 8 patients were enrolled, of which 6 had OBPP and 2 had ICP. Table 5.8 shows both the patient's characteristics (demographic data and pathology) and the information about their sessions with the robot during the experimental period (number of sessions and mean duration). There was a maximum of 15 scheduled sessions for each participant. It can be observed that the number of average sessions per patient in the two months that participated in the experimental group was 11.62 with an average duration of 24 minutes.

Table 5.8: Characteristics of the impaired subjects and the sessions of the experimental period.

#ID	Gender	Age	Pathology	No. of sessions	Duration (mean±SD)
1	Male	4	Left OBPP	15	19.46±2.19
2	Male	10	Left ICP	15	24.64±3.24
3	Female	3	Left OBPP	15	22.26±2.25
4	Male	7	Left OBPP	7	28.85±2.47
5	Female	6	Left OBPP	14	24.92±3.31
6	Female	8	Right OBPP	8	23.50±4.62
7	Male	9	Left OBPP	6	25.16±4.87
8	Male	8	Right ICP	13	24.84±2.51
		6.9 ±2.42		11.6 ±3.93	24.0 ±2.71

In order to carry out the long-term evaluation, 8 pediatric patients were recruited from the VRUH. This section shows the results of the small-N design AB study from a clinical and usability point of view. The first refers to the clinical instruments administered to patients in different stages to measure motor function. The second refers to the results of questionnaires designed with questions on Likert scale (quantitative) and open (qualitative) questions.

5.3.4.1 Clinical Assessment

In relation to the clinical assessment, each measuring instrument was administered 3 times, the first at the beginning of the pre-phase; the second after the end of the pre-phase, coinciding with the start in the post-phase; and the third evaluation at the end of the rehabilitation treatment of the post-phase. Table 5.9 shows the results obtained in the MACS, QUEST and the MALLET scale, related to the assessment of motor function. MALLET instrument measures active abduction, external rotation,

Table 5.9: Clinical results in terms of MACS. MALLET and QUEST scales.

#ID	MACS			MALLET				QUEST			
	1st.	2nd.	3rd.	1st.	2nd.	3rd.	Δ	1st.	2nd.	3rd.	Δ
1	2	2	2	16	16	19	+3	-	-	-	
2	4	4	4	17	17	19	+2	45.12	45.12	48.00	+2.88
3	2	2	2	19	19	20	+1	-	-	-	
4	2	2	2	19	19	19	0	-	-	-	
5	2	2	2	18	18	19	+1	-	-	-	
6	1	1	1	18	18	19	+1	-	-	-	
7	2	2	2	19	19	19	0	-	-	-	
8	4	4	4	13	13	14	+1	41.09	41.09	41.48	+0.39
				17.38	17.38	18.50	+1.13	43.11	43.11	44.74	+1.64
				±2.07	±2.07	±1.85	±0.99	±2.85	±2.85	±4.61	±1.76

movement of the hand to the head, back and mouth. This scale scores from 1 to 25, with 1 being the minimum score and 25 the maximum. The QUEST scale has been applied only in those patients suffering from ICP (patients 2 and 8). For both MALLET and QUEST scales a column (increment symbol Δ) is added to represent the difference or degree of improvement of the second measurement with respect to the third evaluation.

Prior to the analysis of the results, it should be pointed out that although rehabilitation was proposed for patients to go to the hospital twice a week for two months to perform the motor training in each of the two evaluation phases, it was detected that for the pre-phase, patients attended practically all the sessions, whereas the training with the robotic platform (post-phase) was not so. Most of the patients belonging to the post-phase came twice a week, but others only once. This situation was attributed to the fact that participation in the post-phase after the pre-phase, some relatives and caregivers presented more difficulties in accompanying the patient. In relation to the evaluation of the effectiveness of the training, as can be observed by the results of the MALLET scale, the patients did not improve their motor ability after having passed their conventional training, that is after finishing the training in the pre-phase. In contrast, some patients showed an improvement in general ranges after completing their participation in the post-phase, especially those who attended all scheduled sessions. In this sense, they improved between 1 to 3 points. It highlights how patients 1 and 2 with different pathologies (ICP and OBPP in the left limb) who attended all sessions improved 3 and 2 points. Patients who did not present an improvement, were patients

4 and 7 who attended only half of the sessions.

Regarding to the QUEST scale, the patient 2 who presented an ICP in the left limb showed an improvement of almost 3 points, after the motor training with the robotic platform attending to all sessions. Patient 8, however, presenting an ICP in the right limb and attending almost all sessions (13 of 15) presented an improvement of 0.39. H5 was supported by those participants that registered better clinical results.

5.3.4.2 Usability and Satisfaction Assessment

The second part of the evaluation was focused on the usability and satisfaction of patients, relatives and healthcare professionals in quantitative and qualitative aspects. Tables 5.10, 5.11 and 5.12 show the satisfaction and usability results obtained from questionnaires administered to patients, relatives and clinical experts. The valued items are included in the different quantitative dimensions previously described in Table 5.6. In the case of patients and relatives, the questionnaires were filled in the three stages defined in the evaluation procedure, whereas the results of the clinical experts correspond with an evaluation questionnaire answered at the end of the experimental period.

Quantitative dimension

In relation to the patient satisfaction, the Table 5.10 shows the results obtained from the evaluation after administering the patient questionnaire of the different quantitative dimensions. The results refer to the average of the responses of the 8 patients from 0 to 5, with 0 being the worst and 5 being the best result, and their deviations for each of the three evaluations defined in the evaluation design, as shown in Figure 5.8.

According to the results of Table 5.10, the robotic platform was accepted by the patients considering it useful (I.1), with a slight improvement (4.63 out of 5.00 in the third evaluation with an improvement over the second evaluation of 0.38). The patients also considered that it was easy to use, obtaining an improvement in the third evaluation with a value of 4.38 (I.3) in the item that assessed if patients felt overwhelmed by the robot. A 5.00 was obtained when asking if they found it boring (I.4). The results of the patient's questionnaire supported H1, H2 and H3.

In this assessment, it is important to emphasize that the patients, after two months of training with the platform, kept motivated and committed with the treatment. This

Table 5.10: Patient's Results of the Satisfaction and Usability Questionnaire.

Dimension	**Valued item**	**Evaluation with Patients**		
		1st.	2nd.	3rd.
Perceived utility	I.1	4.25±0.89	4.38±0.74	4.63±0.74
Easy to use	I.3	4.13±0.74	4.00±1.20	4.38±0.92
	I.4	5.00±0.00	4.88±0.35	5.00±0.00
Facilitating conditions	I.5	4.63±0.52	3.88±1.13	4.25±0.89
Empathy/ Social Interaction	I.6	4.38±0.92	4.63±0.74	4.75±0.46
	I.8	4.63±0.74	4.63±0.52	4.75±0.71
	I.9	4.63±0.74	4.50±0.93	4.75±0.71

fact was a challenge that arose from the design of the robotic platform, since one of the main causes of the non-adherence to treatment in the traditional rehabilitation was the absence of variety of the exercises, which affected the motivation of the patients. According to the results, these patients, in general, consider that it works correctly in the three evaluations, with a slight improvement (0.38) and obtaining a better score in the first evaluation compared to the third one (I.5). In relation to the evaluation of empathy or interaction, the different scored items had good results, with a slight improvement in the third evaluation, with an average score of 4.75 out of 5.00 (I.6, I.7, I.8). These results supported H4.

Table 5.11 shows the results obtained from the evaluation of the relatives of the patients who participated in the motor training with the robotic platform in the different quantitative dimensions assessed in Table 5.6, in the first, second and third evaluation of the system as was defined in the evaluation design, shown in Figure 5.8. The results are also shown as averages and deviations of the responses (from 0 to 5) of all the relatives.

The robotic platform was also well appreciated by relatives and caregivers. The family valued the robotic platform of a great utility on average, considering that the platform helps their family member to improve doing their exercises (I.1). They consider that it executes better than when starting the training with the robot (I.2). In the three evaluations performed, a slight improvement was obtained in the last evaluation

Table 5.11: Relatives' Results of the Satisfaction and Usability Questionnaire.

Dimension	**Valued item**	**Evaluation with Relatives**		
		1st.	2nd.	3rd.
Perceived utility	I.1	4.25±0.89	4.38±0.74	4.50±0.53
	I.2	4.00±0.93	4.25±0.89	4.50±0.93
Easy to use	I.3	3.88±0.99	4.00±0.93	4.50±0.93
	I.4	3.88±0.83	4.13±0.83	4.13±0.83
Facilitating conditions	I.5	3.88±1.13	4.00±1.07	4.13±0.83
Empathy/ Social Interaction	I.6	3.75±1.16	4.38±0.52	4.00±0.93
	I.7	4.50±0.93	4.75±0.46	3.88±1.36
	I.8	4.00±0.93	4.25±1.16	4.50±1.07

with a value of 4.5 out of 5 in both items after finishing the training and getting to know the robot better. These results supported H1.

Family members and caregivers stated that the platform was easy to use, highlighting a slight improvement also in the third evaluation in the two items corresponding to whether they felt overwhelmed and whether the exercises were boring, with a score of 4.50 and 4.13 respectively (I.3, I.4), supporting H2. Also, relatives in general consider that the robot works correctly, with a slight improvement on average in the third evaluation with a score of 4.13 compared to 5.00 (I.5), supporting H4.

Finally, relatives valued positively the social empathy that the robot gets (I.6, I.7, I.8), given that they consider that their children like to interact with it, obtaining an average score of 4.00 after finishing the treatment. This value is slightly improved (0.25) compared to the first evaluation at the start of treatment, but decreases compared to the second evaluation (0.38). This fact is also repeated in the valued item of motivation to come to the hospital to perform the training. The best score is obtained in the second evaluation (the month of using the robot with a score of 4.75) which descends in the third with a score of 3.88 (0.87). This decline could be attributed to the fact that the routine may decrease some interest, hence the need to develop new games, etc. that empathize with children and motivate them continually.

The professionals who participated in the piloting were: experts 1 and 2 were physiatrist, and expert 3 was a therapist. The assessment was done through a ques-

Table 5.12: Experts' Results of the Satisfaction and Usability Questionnaire. The Valued item is described in Table 5.6.

Dimension	**Valued item**	**Evaluation with Clinical Experts**			
		E.1	E.2	E.3	Mean±SD
Perceived utility	I.1	4	4	5	4.33±0.58
	I.2	4	4	5	4.33±0.58
Easy to use	I.3	3	4	4	3.67±0.58
	I.4	5	3	4	4.00±1.00
Facilitating conditions	I.5	5	4	5	4.00±1.00
Empathy/ Social Interaction	I.6	4	4	5	4.33±0.58

tionnaire centered on the questions of Table 5.6. These professionals valued in a global way and at the end of the evaluation process. Table 5.12 shows the valuations by each of the experts and in the last column of the Table 5.6, the average value and standard deviation of the three professionals for each of the items evaluated.

Table 5.13: Experts' Results of the Open Questions provided in the Questionnaire. The Valued Question is described in Table 5.7.

Valued Question	**Evaluation with Clinical Experts**		
	E.1	E.2	E.3
Q.4	Not sure, because we do not have enough sessions and patients to have conclusions.	Yes, most patients have improved shoulder flexion and abduction	Yes, Some children have improved flexion/extension and others the rotation. Some relatives believe that patients have improved the quality of the movement.
Q.5	Yes	Yes	Yes

According to the results of Table 5.12, the robotic platform was also well accepted by healthcare professionals. Specifically, healthcare professionals rated the perceived utility dimension with a 4.33 out of 5.00 on the two valued items of whether they believe it helps and how best to perform the exercises after training with the robot (I.1, I.2). The involved professionals also consider that patients were not overwhelmed by the robot (3.67 from I.3) and they were not bored (4.00 from I.4). Regarding the facilitating conditions, they valued with a 4.00 about 5.00 the item that the robot worked correctly (I.5). The experts also positively evaluated the empathy dimension or social interaction of the robot, considering that patients like the robot with a score of 4.33 out of 5.00 (I.6). The results of the experts' questionnaire were consistent with H1, H2, H3 and H4.

Qualitative dimension

In relation to the qualitative evaluation, Table 5.14 shows the results of the evaluation of the patients to the questions about which part of the training they like the most (Q.2) and which one is more difficult (Q.3). In relation to Q.2, in the three evaluations they did not change their opinion, resulting in average the second part of the training the part that they like (75%). Regarding to Q.3, in the first and second evaluation the part that they considered more difficult on average is the first one with a percentage of 62.5%, coinciding with the part that they like less. In the third evaluation, a patient changed his/her opinion and said that Simon game was the part that was more difficult and at the same time he liked more. However, in the third evaluation, the part that was still considered as the most difficult was the first one. These results contributed to give credibility to the hypothesis that through play, the child feels more motivated and uninhibited, supporting H3.

Table 5.14: Patient's Results of the Open Questions provided in the Questionnaire.

Valued Question	**Evaluation with Patients**			
	Activity	1st.	2nd.	3rd.
Q.2	Mirror	25%	25%	25%
	Simon	75%	75%	75%
	None	0%	0%	0%
Q.3	Mirror	62.5%	62.5%	50%
	Simon	25%	25%	37.5%
	None	12.5%	12.5%	12.5%

Regarding the open question of what new things they would like the robot to do (Q.1), the answers are diverse. Among them, it is mentioned that they would like to eat ice cream together, to dance (five times), to play football (six times), to sing (four times), to run or to improve the robot movements. Almost all the answers are related to playing games.

The relatives and caregivers also had the opportunity to openly show their opinions about the platform. Table 5.15 shows the results of the qualitative evaluation carried out by the relatives on the items: whether they have detected any improvement (Q.4) and whether they would like their children to continue training with the robot (Q.5). The results shows that from the second evaluation, they detected that the patient had improved when performing the training with the robot. Specifically, 62.5% stated that their children had performed movements that they had not been able to perform before (Q.4). In all evaluations all relatives agreed that if the robot was available, they would like to continue participating (Q.5). These results supported H1 and H3.

Table 5.15: Relatives' Results of the Open Questions provided in the Questionnaire. The Valued Question is described in Table 5.7.

Valued Question		**Evaluation with Relatives**		
		1st.	2nd.	3rd.
Q.4	Yes	25%	62.5%	62.5%
	No	75%	37.5%	37.5%
	Not sure	0%	0%	0%
Q.5	Yes	100%	100%	100%
	No	0%	0%	0%
	Not sure	0%	0%	0%

In relation to the open question of "what new things you would like the robot to do" (Q.1), the relatives answered that they would like, among others, that the robot could perform manual pressure exercises, more variety of games, longer sessions with more exercises to train lower limb, crawling, dancing, functional activities of daily life, dressing, etc., to be taken into account for future developments of the system.

Finally, clinical experts also qualitatively evaluated the robotic platform through the TAM questionnaire on the acceptance of the technology, adapted to the health professional profile. The answers of the three experts can be seen in Table 5.13.

According to Q.4, two of three healthcare professionals considered that most patients had improved some motor skills after this study, while one professional stated that they could not be sure of that, since it is needed more patients and more time to have conclusions. These results were consistent with H1. In relation to the question that if they would like the patients to continue with the therapy provided by the robot (Q.5), all agree that yes.

In relation to the open questions, responding to the proposal of new activities (Q.1), the evaluated professionals indicated that it would be very interesting to include a greater variety of dances and choreographies, more interactive games involving legs to improve the mobility of the joints. For instance, working on grasping objects, shoulder rotations, the possibility include virtual reality, etc. By contrast, one of the physiatrists replied to this question that it is fine as it is. The professionals also listed other applications for which the platform would be successful from their point of view, such as cognitive stimulation and affinity in treatment, assistance at home, habits education or motor and mental games for children.

5.3.5 Discussion

The NT robotic platform for motor rehabilitation was validated by carrying out a small N-Design AB trial, where the participants of the experimental condition were also involved in their control condition. The advantage of small-N design is that allows clinicians to identify features relevant to every individual performance. In total, 8 pediatric patients were recruited suffering from ICP and OBPP. A trained therapist was in charge of deploying and operating the platform, while engineers were supporting him remotely. The participants were assessed in three different stages of the trial by administering clinical scales and satisfaction and usability questionnaires.

According to the MALLET and QUEST scales, patients presented a slight improvement in their motor skills after their training with the robotic platform compared to conventional treatment, where no improvements are detected. This is especially evident in those patients who attended all scheduled sessions. In relation to the evaluation of the acceptance of the technology, patients, relatives and health professionals consider it very useful, easy to use and with correct operation. It should be noted that the relatives consider that the patients performed the exercises better than before training with the robot (score 4.50 with respect to 5.00). This point of view is also supported by healthcare providers by getting an score of 4.33 out of 5.00. Finally, relatives in general consider patients to be more motivated to attend the hospital when having sessions with the robot.

Regarding the qualitative evaluation, 62.5% of the families or caregivers report that their relative patient performed movements that they were not able to perform previously; and 66.6% professionals of the health professionals state that patients had improved their powered upper-limb rehabilitation by the robotic platform. Finally, family members and health professionals agreed 100% that they would like their child to continue with the motor training using this platform.

5.4 Episode 3: Hand-Arm Bimanual Intensive Therapy

Child neurorehabilitation therapies seek to achieve the recovery of damaged neuronal zones and atrophied muscles by the repetition of different therapeutic exercises, both physical and cognitive. There is a special modality of these therapies, which are currently in the ascendant, for children with psychomotor problems, in the form of Intensive Therapy Camps, such as the Hand-Arm Bimanual Intensive Therapy (HABIT) [Charles et al. 2006], created at Columbia University. The goal of HABIT is to help children to improve the dexterity and coordination of both arms in daily functions. Intensive neurorehabilitation therapies following the HABIT methodology have demonstrated to be very effective [Gordon et al. 2007]. The success is due to the application of daily intensive training based on many repetitions with exercise variability [Magill et al. 1990], progressive increase of complexity, motivation [Kleim et al. 2008], and positive feedback [Schmidt 1988]. These concepts also represent the needs of pediatric patients in this rehabilitation process.

5.4.1 HABIT Summer Camp

HABIT was accomplished in the form of a summer camp of 20 consecutive days, instead of weekly sessions as the long-term evaluation done before. It is especially aimed at patients with hemiplegia and ages between 5 and 13 years. During the camp, the children performed a multitude of therapeutic activities, hidden under a relaxed atmosphere of game. These activities, in turn, were designed to respect the individualized treatment, being personalized according to the needs of each patient. In the summer of 2017, the HABIT camp was implemented for the first time in Spain. This camp was held at the European University of Madrid (UEM) and 10 patients and 14 volunteer therapists/physiotherapists participated. Rehabilitation focused on the affected limb/s of the patient and trained daily for more than 6 hours. In some cases there was more than one therapist per patient. This therapy scheme is challenging to keep the patient engaged and motivated. Unlike other methodologies, intensive therapy punishes the patient's mood and can negatively compromise adherence to treatment.

The intensive therapy methodology presented a more demanding scheme that involved a development effort to achieve active engagement and meet the daily needs of the patients. The robotic platform was deployed for 10 days, treating 10 patients and being used by the 14 therapists. At the end of the camp, 110 clinical sessions were satisfactorily executed. Figure 5.9 shows one of these patients playing with NAOTherapist platform during HABIT camp. The evaluation process was designed following the methodology explained in Section 3.5, based on the USUS framework [Weiss et al. 2009]. Data collection was exhaustive during those days: questionnaires for both patients and therapists, session logs, sensor data capture, discussion groups and interviews.

Figure 5.9: Patient interacting with NAOTherapist platform in HABIT.

5.4.2 Objectives

The goal of the incorporation of NAOTherapist in the HABIT camp was to increase the type of activities that the kids can perform, through providing sessions with the robot. Since these sessions were held in consecutive days, it was very important to design a type of interaction able to maintain the child motivation along these days and offer therapists the possibility to configure and execute the sessions by themselves. For this, prior to the camp, a requirements analysis and a system improvement of several months were made incorporating the new functionalities to the platform, such as: configuration interface, gamification mechanics, adaptive reward system, new configurable parameters, as well as new interactive activities with the robot (see Table 5.1).

This evaluation episode aims to demonstrate that the NAOTherapist platform is capable of maintaining the engagement and high commitment in a demanding environment such as intensive therapy with daily rehabilitation sessions, in which the system must deal with the novelty effect (loss of interest in the robot).

5.4.3 Experimental Design

The HABIT rehabilitation camp lasted 21 days and was held between July 13 and August 2, 2017. The training sessions were 5-6 hours, and took place every day at the European University of Madrid, from Monday to Saturday. A total of 10 children aged 5 to 13 years old affected by cerebral palsy attended the camp. Each patient was assigned a personal therapist/s who accompanied them during the therapeutic activities, most of which were transformed into a game. One of these activities consisted of a rehabilitation session with the NaoTherapist platform, lasting approximately 20-30 minutes, which was carried out once a day for 11 days (10 exercise sessions + 1 calibration). This section describes the entire experimental process that was carried out for the collection of participant data.

5.4.3.1 Procedure Design

Before beginning the study, clinical professionals were trained to use the platform. In a previous meeting they were introduced to the robot and learned how to use the graphical interface that configures the sessions and executes the system. From the first moment, the idea was that the therapists were able to manage the platform by themselves. All sessions followed the same procedure, which is defined in the Figure 5.10.

Once the study began, the schedules assigned to each patient were established daily. Therapists accompanied them to the room where they carried out the activity with the robot. Once there, therapists were in charge of setting up the session for their patients. For this, they selected 2 or 3 gamified activities. The available games were: *mirror, memory, inverse memory, Nao says, dance with me and teach me*. Although the therapists were totally free to choose any of these games, the most common session consisted of: *mirror, memory and Nao says*, except the last session that was decided to play *dance with me*. After this selection, therapists had to adapt the activities and establish progressions that guaranteed the patient's improvement, that is, the poses, mimics and requests from the robot could be more demanding if they saw a favorable patient's progress. Finally, this configuration was saved and the session was started.

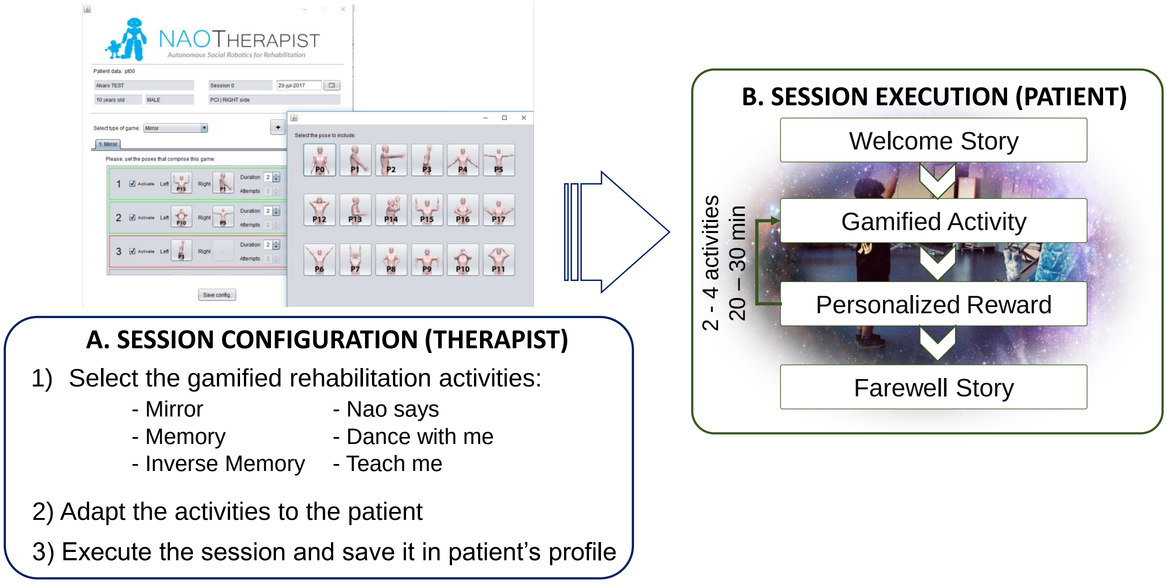


Figure 5.10: 2-step session procedure: A. configuration and B. execution.

During the session execution, patients stood about 1.5 meters from the robot which was initially sleeping in different positions. To increase the variety, the patient could find the robot sometimes sitting, sometimes lying down or even squatting. The RGB-D sensor was located just behind the robot. Therapists were located next to configure and, if necessary, to give indications to the patient. The execution of the robot was completely autonomous, so there was neither teleoperation nor any kind of human intervention. The structure of the use case followed the explained model of the Figure 4.1 in Section 4.1, in which every session began and ended telling a story, which helped to improve the patient's immersion in the activity. The robot told them that he came from another planet. Due to an accident, his spaceship had crashed, and he needed their help to be able to self-repair and reconfigure his circuits. To do this, the exercises proposed by the robot were the key to getting back to his planet. A change of roles was raised in which for the first time the patient was the one who helped the robot. Patients always answered affirmatively to: "*do you want to help me?*" and they were very committed to this task. Every day the story continued and the robot gave more and more details about his planet and how much they were helping him.

The sessions lasted between 20 and 30 minutes and were composed of 2 to 4 gamified activities that the therapist had previously selected. After each activity, the robot rewarded the patient with a personalized reward or paused to rest. The rewards were adapted to patient preferences. This was a key point as a proposal to improve motivation and adherence to the activity. The system considered the number of attempts the patient had needed to complete the exercise multiplied by a random value. This determined the probability that the reward was very good, good or instead, a rest was made. The idea was that patients were aware of the effect-reward paradigm explained in Section 3.2. The more effort during the activity, the better and more related would be the reward received. Only in this way, it could be guaranteed that the patient was motivated to improve their progression throughout the study.

5.4.3.2 Materials

For the data collection, quantitative and qualitative methods were used in different phases and from the perspective of patients and clinicians. The materials were:

- Questionnaires and structured interviews. Three pairs of questionnaires (for clinicians and patients) were designed for each of the evaluation phases: pre-evaluation, post-session and post-evaluation. In total 6 questionnaires with items based on the Likert scale (from 1: do not agree to 5: do fully agree) and open questions. Except for the pre-evaluation questionnaire, the design and purpose of the different questions was aimed at evaluating each of the USUS framework factors: perception of usability, social acceptance, user experience and social impact of the NAOTherapist platform. The pre-evaluation was aimed at collecting demographic data of patients as well as their previous experience with technology.
- Objective data. During the patient-robot sessions, the perception system collected the angles of the patient's joints and the evolution of the thresholds throughout the rehabilitation activities. Thresholds implicitly determine the patient's ability to improve and adapt to the platform. The initial threshold of each pose is calibrated for each patient in session zero. As explained in Section 4.7.1, this value is used to determine whether the patient's pose is determined to be correct or not. Therefore, to state that patients have improved in activities, it would be determined by a decrease in their threshold values. It was also of interest to collect the number of attempts and other logs of the session flow.
- Observations. The observations recorded by the experts who were present throughout the study were also taken into account. Throughout the sessions, their impressions about the robot-patient interaction were collected as potential improvements of the system.

5.4.3.3 Hypotheses

According to the USUS evaluation factors and the purpose of this study, the following hypotheses were defined:

- **H1. Usability**: Is NAOTherapist usable?
- **H2. Social Acceptance**: Is NAOTherapist accepted by the participants (patients and healthcare professionals)?
- **H3. User Experience**: Do participants have good experiences when interacting with NAOTherapist platform?
- **H4. Social Impact**: Is the impact of NAOTherapist in the society positive?
- **H5. Patient Improvement**: Do patients improve in NAOTherapist activities throughout the study?

5.4.3.4 Study Protocol

This section describes the HABIT evaluation procedure relating the phases with the materials administered to evaluate the USUS factors. Figure 5.11 describes this relationship between phase, material and evaluation factors. This procedure was designed and applied in HABIT in order to cover all the key aspects of evaluation through a SAR adaptation of an existing framework (Section 3.5).

The study differentiates three chronologically ordered evaluation phases: pre-evaluation (Pre.), post-session (PS.) and post-evaluation (PE.). The pre-evaluation phase aimed at collecting demographic data of patients, as well as their previous experience in technology through interviews and questionnaires (P. Pre. and T. Pre.). The results of this initial evaluation are presented in Sections 5.4.3.6 and 5.4.3.5. After the pre-test, a presentation of the platform was made to the clinical professionals before starting the HABIT camp. The patients had a zero calibration session with the platform to initialize all threshold values associated with each patient.

The second evaluation phase was carried out after each session. Both professionals and patients filled out their corresponding post-session questionnaire (P. PS. And T. PS.). The objective of these questionnaires was to evaluate the factors of utility, social acceptance and user experience, as well as to collect comments and improvement suggestions for the next sessions. Thus, if something in the session was not going well, it could be solved for the following ones. During this phase, the system also collected

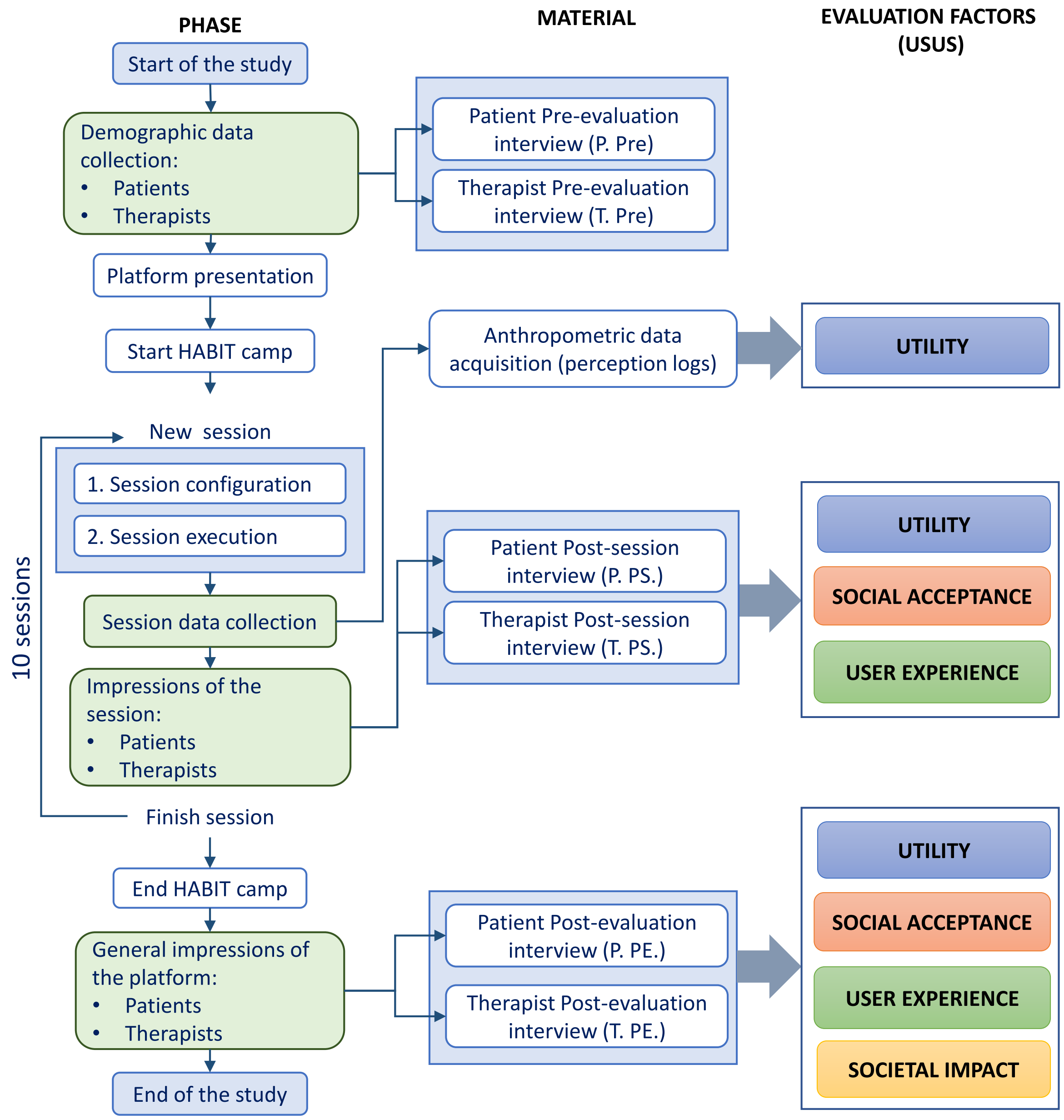


Figure 5.11: HABIT Evaluation Procedure based on USUS framework, described in Section 3.5.

the anthropometric data of the patients (perception logs), that is, the angles of the patients' joint skeleton and the progression of the threshold throughout the sessions (explained in Sections 4.7.1 and 4.5). These patient data aimed to demonstrate the usefulness of the prototype in terms of how the patient learns and improves in activities with the robot. The last phase was called post-evaluation and not only raised more global questions about the experience of patients and experts, but also asked about the future potential of the tool and the impact on society and their jobs. Through questionnaires, interviews and open questions both groups responded to the four USUS factors: utility, social acceptance, user experience and social impact.

5.4.3.5 Patients

In the last update of the use case, the platform was adapted to the pathology treated in HABIT, Infantile Cerebral Palsy with hemiparesis (only one side was affected). The group of patients was quite homogeneous in terms of clinical condition, except for a particular case that also had a certain cognitive deficit. The inclusion and exclusion criteria were aligned with those of HABIT, so that all patients were eligible to enjoy the sessions with the robot without exception. The criteria to consider were:

Inclusion criteria:

- Patients aged 5 - 14 years suffering from ICP and hemiparesis.
- Recruited for the HABIT summer camp at UEM.
- Clinically stable and capable to start the treatment.
- Authorization by their parents or guardians with the corresponding signed agreement.

Exclusion criteria:

- Visual difficulties.
- Pain that makes it impossible to perform exercises.
- Other associated neurological pathologies.

Table 5.16 shows the 10 patients who were chosen as participants of the first HABIT camp in Spain, of which 80% were males. The average age of the patients was 8.6 and SD 2.0 with a difference of 6 years between the smallest and the oldest, being almost two years older than in the previous long-term study. Another peculiarity of the study was that one of the participants was Italian and he had a therapist who helped him with the translation of the explanations. This fact occurred especially at the beginning, throughout the days the patient perfectly understood what he had to do and the therapist assisted him only in the translation of the storytelling that the robot offered daily. All participants completed 10 sessions with the robot except P10 who had to interrupt the treatment in the middle of the camp for personal reasons. Likewise, the last column of Table 5.16 relates each patient to their therapists. Having more than one therapist depended on the needs of the patient and the workload that could be assumed by them. Importantly, the therapists in charge were those who configured, monitored and evaluated the patients during the study with the NAOTherapist platform. They were also responsible for monitoring and responding to the questionnaires related to their patients. P10 will not be considered in the evaluation results.

Table 5.16: Patients that participated in the study.

ID	**Gender**	**Age**	**Nationality**	**Affected Side**	**Sessions Completed**	**Therapist/s in charge**
P01	Male	8	Spanish	Right	10	T04
P02	Male	12	Spanish	Right	10	T14
P03	Male	9	Spanish	Left	10	T02, T09
P04	Male	7	Spanish	Left	10	T05, T09
P05	Male	6	Italian	Left	10	T06
P06	Female	9	Spanish	Left	10	T03, T13
P07	Female	11	Spanish	Left	10	T01, T12
P08	Male	6	Spanish	Left	10	T07, T08
P09	Male	8	Spanish	Left	10	T10, T11
P10	Male	10	Spanish	Left	5	T11

With the objective of collecting more data about the participants, a questionnaire about their previous experience in technology was made before starting the study. The objective was to determine their degree of acceptance towards technology in therapy and if they had previous experiences that could condition them. The results of this questionnaire are based on Likert scale (1-5), shown in Table 5.17. Regarding the use of technological devices, 70% of the patients had used tablets, 50% smartphones and 40% computers. Everyone used these devices almost daily (4.1 ± 0.99). Their experience in therapy had been positive since everyone recognized that they liked it (4.75 ± 0.79). On the contrary, hardly any of them had used some kind of technological device during their rehabilitation (0.3 ± 0.48) and none had done any kind of robotic therapy. Except for PT04 who declared being afraid of robots, all participants said they would like to do their therapy with a robot and even have it at home. A very interesting evolution was that of the PT04 patient who, in addition to recognizing his fear in the pre-test, in the first days he felt insecure with the NAO robot, but over time he ended up creating very strong emotional ties with it.

Table 5.17: Pre-test administered to participating patients to determine their previous experience and perception of technology (Likert scale 1-5).

Q. ID	**Interview**	**Description**	**Mean**	**SD**
Q1	P. Pre	Do you usually use technological devices, such as:	2.15	1.71
		tablets?	70%	
		computers?	40%	
		smartphones?	50%	
Q2	P. Pre	How often do you use these devices? 0 (rarely) - 5 (daily)	4.1	0.99
Q3	P. Pre	Do you like to do therapy?	4.75	0.79
Q4	P. Pre	Have you used any technological device when you receive therapy?	0.3	0.48
Q5	P. Pre	Do you know what a robot is?	4.5	1.05
Q6	P. Pre	Have you ever used a robot in your therapy?	0.0	0.0
Q7	P. Pre	Would you like to use a robot in your therapy?	4.25	1.68
Q8	P. Pre	Would you like to have a robot at home?	4.5	1.58

5.4.3.6 Clinical Professionals

The group of health professionals consisted of 14 volunteers who had a relationship with UEM, see Table 5.18. The average age was 25.6 ± 6.25. 43% of the professionals were students: 4 were physiotherapy students (T01, T06, T09 and T11) and there was also a doctoral student (T05). The rest of volunteers worked as physiotherapists (T02, T07, T08, T10, T14) or as occupational therapists (T03, T04, T12). One of the therapists had also studied psychology and other physical education. As shown in Table 5.18, the background of the volunteers was quite heterogeneous within the scope. This was considered very positively, since the platform would be evaluated from different perspectives and all of them important in the field of rehabilitation. All professionals were Spanish nationals except T06 who was Italian and responsible for supporting the Italian patient.

Table 5.18: Healthcare professionals that participated in the study.

ID	**Gender**	**Age**	**Nationality**	**Education**	**Employment**
T01	Female	24	Spanish	P. S.	S.
T02	Female	23	Spanish	P.	P.
T03	Female	36	Spanish	P./ O.T.	O.T.
T04	Female	30	Spanish	O.T.	O.T.
T05	Male	26	Spanish	F. / PhD. S.	P. / R.P.
T06	Female	26	Italian	P. S.	S.
T07	Female	24	Spanish	P.	P.
T08	Male	25	Spanish	P.	P.
T09	Female	44	Spanish	Psy. / P. S.	S.
T10	Female	22	Spanish	P.	P.
T11	Male	23	Spanish	P.E. / P. S.	S.
T12	Female	22	Spanish	O.T.	O.T.
T13	Female	23	Spanish	O.T.	S.
T14	Female	24	Spanish	P.	P.

P. - Physiotherapist
S. - Student
O.T. - Occupational therapist
R.P. - Research professor
Psy. - Psychologist
P.E. - Physical education

A pre-test was also done with the therapists pursuing the same objective: to determine their previous experience with technology, their perception about how a robot can help in therapy and if in their point of view, it could be difficult to learn to manipulate it. This test was administered the day of the platform presentation to the professionals, but before having any information about the system. The results are shown in the Table 5.19.

50% of professionals used tablets, 85% had experience with computers and 92% had smartphones. They all used these devices daily. This result is quite consistent

Table 5.19: Pre-test administered to participating clinicians to determine their previous experience and perception of technology (Likert scale 1-5).

Q. ID	Interview	Description	Mean	SD
Q1	T. Pre	Do you usually use technological devices, such as:	3.35	1.56
		tablets?	50%	
		computers?	85%	
		smartphones?	92.3%	
Q2	T. Pre	How often do you use these devices? 0 (rarely) - 5 (daily)	5.0	0.0
Q3	T. Pre	Do you usually innovate in your rehabilitation sessions?	3.27	1.34
Q4	T. Pre	Have you used any technological device to provide therapy?	2.35	1.15
Q5	T. Pre	Have you ever manipulated a robot?	1.28	0.61
Q6	T. Pre	Do you think it is easy to manipulate a robot?	3.42	0.64
Q7	T. Pre	Do you think it would be useful to use a robot in pediatric therapy?	3.64	0.63
Q8	T. Pre	Do you think a robot can replace a therapist in their job?	1.42	0.75

considering the average age (25.6) of the experts. Regarding the question of whether they used to innovate in their rehabilitation sessions, some of them responded affirmatively (3.27 ± 1.34), although few acknowledged having used the technology to improve treatment adherence (2.35 ± 1.15). The most used device was the Wii game console and the sports games and balance board pack. As for using a robotic platform for therapy, only one therapist says that he has used the Lokomat, a robotic gait orthosis equipped with a modern body weight discharge system [Jezernik et al. 2003]. None had used a social robot or virtual avatar that interacts socially with the patient. Most experts were optimistic as to whether they believed it would be easy to manipulate a robotic platform (3.42 ± 0.64), which is also consistent because it is a sample with considerable experience in the use of technology. Regarding whether they believed that the platform could be useful in pediatric therapy, most thought it was a very good option (3.64 ± 0.63) for both to improve motivation and adherence to children's treatments.

Regarding the fear of being replaced, they all considered that a social robot could never replace the therapist at work (1.42 ± 0.75), although they did recognize that there were mechanical tasks that could ease their work or was useful as an automatic mechanism for patient evaluation.

5.4.4 Evaluation Results

In order to test the hypotheses raised, this section summarizes the main results of the evaluation of the NAOTherapist platform in the HABIT camp. The following sections are organized based on each of the target criteria: Usability (Section 5.4.4.1), Social Acceptance (Section 5.4.4.2), User Experience (Section 5.4.4.3), Societal Impact (Section 5.4.4.4). 9 patients and 14 clinical professionals were fully involved in this camp. A total of 90 sessions + 10 calibration sessions were executed and evaluated and all of them were carried out without any incident. The results related to the post-session phase are average values of all the questionnaires filled out after each session. In the post-evaluation phase, a single questionnaire was filled out per participant about their general opinion of the experience. Other consideration was that patient P10 had to leave the camp in half, so he was not taken into account for the results of the study.

5.4.4.1 Usability

Determining whether the platform NAOTherapist is usable or not, responds to the hypothesis: "H1. Usability: Is NAOTherapist usable?". Usability is probably one of the most important evaluation factors of this study. It is defined by [ISO 9241-11 2017] as *"the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use"*. This section also deals with the hypothesis: "H5. Patient Improvement: Do patients improve in NAOTherapist activities throughout the study?". In order to evaluate this factor, it is subdivided into a set of indicators: effectiveness, efficiency, learnability, flexibility, robustness and utility.

Effectiveness

Effectiveness is defined as *"the accuracy and completeness with which users achieve specified tasks"* [ISO 9241-11 2017]. In other words, the ability of the system to perform the task for which it is designed. In our case, it is necessary to evaluate that

NAOTherapist is capable of providing robotic rehabilitation sessions and that these sessions are carried out effectively, having an impact on the patient. Therefore, the patient's objective progress is considered a relevant indicator as a factor of effectiveness. This objective value is calculated through the recollected data of the patient through the perception system: the range angles of the joints and the evolution of the threshold values of the poses. Similarly, the number of corrections, attempts and improved poses provide very relevant information about the evolution of patients. For all the rehabilitation sessions developed, the distances between the poses, the resulting thresholds after the completion of each of these have been collected, and a label that indicates whether the corresponding pose was performed correctly or not. In addition, the threshold information was then organized by patient, session and pose, being able to observe the improvement presented by each patient in each pose. These relevant data of the sessions executed are shown for each patient in Table 5.20.

Table 5.20: Questions related to the factor of effectiveness.

Patient	Pose Attempts	% Poses Corrections	Improved/Retrogress Poses	Affected Arm Progress	Average Progress
pt01	552	21.74%	26/3	12.45%	13.90%
pt02	496	23.19%	20/9	2.78%	8.95%
pt03	575	20.52%	26/4	18.44%	18.25%
pt04	629	34.02%	7/24	-21.93%	-24.58%
pt05	527	22.58%	28/6	10.10%	12.25%
pt06	547	24.50%	21/9	9.29%	10.54%
pt07	447	20.58%	33/1	19.46%	17.77%
pt08	270	40.00%	19/12	7.68%	6.44%
pt09	551	28.16%	17/14	4.56%	3.59%
	510.44 ± 103.23	26.14% ± 0.06	21.88 ± 7.52/9.11 ± 7.01	6.98% ± 0.12	7.46% ± 0.12

Looking at the results presented in Table 5.20, a general improvement of participants is stated. The data presented is coherent, being able to see how the percentage of failed attempts is inversely proportional to the average progress. The improved/retrogress poses refer to the number of poses in which the patient has finally improved or worsened. The results obtained for each child are not entirely comparable to each other. This is because each patient performed sessions adapted to their needs, also designed by different therapists. Then, the progression is dependent, externally to the platform, of the therapist and the unique characteristics of each child.

Before beginning the analysis of the patient's progress, it is important to remember what information is captured by the platform during the rehabilitation sessions and how it is treated. Perception system captures the nearest user in front of the RGB-D sensor, also generating an anthropometric model of joint angles. When the robot indicates a pose to be performed, the target pose is compared with that set by the patient, obtaining a distance between them. Then, this distance is compared with a threshold corresponding to the pose and the patient, which is adjusted according to the correctness of the pose (more info in Section 4.7.1).

Therefore, the information to observe the patient's progress is based on this adaptive threshold, which will be reduced throughout the therapy if the patient really shows an improvement in the mobility of the affected area. According to the results in Figure 5.12, 90% of the patients improved from 5% to 15% in their affected arm and also in the general average progress. Only one patient did not obtain such improvement due to his cognitive characteristics, since throughout the sessions an emotional bond was created so intense that he preferred to interact verbally with him, neglecting his training quality. This fact, although a priori may seem negative, the therapist in charge saw it as a productive situation to work with the patient. The degree of concentration was so high that although the patient did not pay attention to the poses, the intensity of the therapy could be maintained without the need for robot corrections. Which greatly increased the potential of the platform.

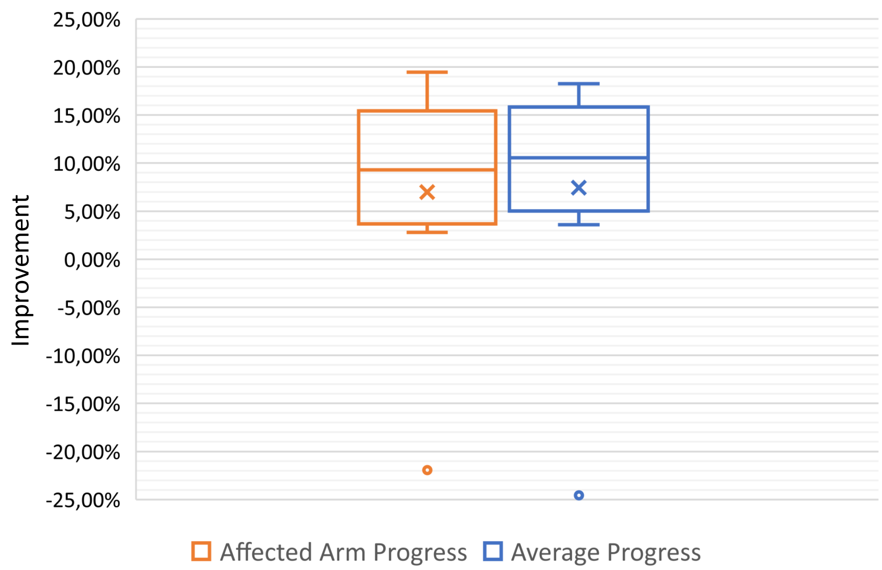


Figure 5.12: Objective effectiveness indicator based on the patient's progress.

Apart from the objective data, the opinion of the clinical professionals is also very relevant. Therefore, an open question (T.PE.Q21) is also formulated in the post-evaluation test to determine whether the patient has improved in some functional, cognitive or motivational aspect. 70% of therapists detected an improvement in their patients in terms of joint range, gross motor fluidity, motivation, attention and cognitive processing. 18% of the experts did not perceive any apparent improvement that could be attributed to the use of the platform, but to the general methodology of the camp. The remaining 12% did not express their opinion about it.

Efficiency

The [ISO 9241-11 2017] defines efficiency as *"the resources expended in relation to the accuracy and completeness with which users achieve goals"*. In this study case, resources and costs to reach the goals are related to the fluency of the patient-robot interaction. This interaction must be fluent enough to minimize the time/cost of the session. However, a global time value cannot be established, since the interaction is a perception dependent on the abilities of each patient.

Asking for efficiency or the fluency concepts is a complicated question for the child. Therefore, this was formulated to the therapists in charge in each post-session questionnaire (T.PS.Q7) and in the global evaluation of the post-evaluation questionnaire (T.PE.Q2). The answers to these questions are shown in Table 5.21. According to the 5 point Likert scale (1 strongly disagree to 5 strongly agree), in both cases a very fluent interaction was considered, obtaining results of 4.32 ± 0.69 in the cumulative average of all sessions and 3.88 ± 0.62 in post-evaluation. With a difference of 0.44, it seems that the therapists had a slightly worse perception when assessing the fluency of the interaction from the overall experience with respect to the accumulated throughout the study. In the first case, it represents an average value of 90 questionnaires at different times and secondly 14 questionnaires at the end of the study.

Table 5.21: Questions related to the factor of efficiency.

Q. ID	**Interview**	**Description**	**Mean**	**SD**
Q7	T. PS	Has the child-robot interaction carried out fluently?	4.32	0.69
Q2	T. PE		3.88	0.62

Learnability

The USUS framework defines learnability as *"how easy can a system be learned by novice users"* [Weiss et al. 2009]. This indicator is evaluated as the ease that patients have to understand the task with the robot, both the objectives and the way to achieve them. To do this, this question is proposed to patients and therapists in each post-session questionnaire and more globally as a question in post-evaluation phase.

Regarding the results, Table 5.22 summarizes the mean and standard deviation of the therapists (T.PS.Q4 and T.PE.Q1) and patients (P.PS.Q6 and P.PE.Q1/Q2) responses in the different evaluation phases. The two groups determined that the patients were able to perfectly understand the task with the robot with values above 4.0. Patients were also asked if the robot's poses were easy to understand/imitate (P.PE.Q2), the result obtained was 3.56 $\pm$ 1.01 since they expressed having some difficulties on imitating certain postures suggested by the robot. The heterogeneity in age and height made the size of the robot could be small in some cases or placing it on the ground, having a more complex perspective for imitation.

Table 5.22: Questions related to the factor of learnability.

Q. ID	Interview	Description	Mean	SD
Q4	T. PS	Do you think the children understood what they had to do?	4.36	0.76
Q1	T. PE		3.94	0.68
Q6	P. PS	Was it easy to understand how to play with the robot?	4.37	0.81
Q1	P. PE		4.33	1.00
Q2	P. PE	Was it easy to understand the poses from the robot?	3.56	1.01

In NAOTherapist, learnability is also related to the patients' improvement, since it means they learn the activities. Therefore, it is important to note that part of the results of Table 5.20 of the effectiveness indicator are also shared here. As mention before, 90% of the patients suffered an improvement according to the objective data. The number of improved poses was 21.88 $\pm$ 7.52 much higher than 9.11 $\pm$ 7.01 of retrogress poses.

Finally, all patients without exception found the robot's explanations clear and easy to follow. The feedback offered by the platform was clear and facilitated the postural control of patients. The interaction design encouraged patients to learn and improve their activities.

Flexibility

According to the USUS framework, flexibility is defined as *"the capability to carry out a variety of tasks in unstructured environments and adapt to situations"* [Weiss et al. 2009]. In other words, the different capabilities and forms of adaptation provided by the system to achieve the objectives. As mentioned above, NAOTherapist has the ability to give a coherent response to the patient's actions. The two interaction channels used by the system are verbal and visual, both for the natural course of activities and to provide feedback to the user. Therefore, the flexibility of NAOTherapist is determined by evaluating the capabilities of the platform to guide patients through their interaction channels to achieve the objectives.

According to Table 5.23, two questions to the therapists were formulated regarding the flexibility of the platform. The first (T.PS.Q6) was asked after each session, if the robot had guided correctly to correct the patient's postures. The average accumulated value is 4.06 ± 0.83, so the therapists unanimously considered that the robot's feedback was useful for the patient. In the post-evaluation phase about the ability to adapt the platform to the patient's conditions (T.PE.Q6), they responded that the platform was mostly adapted, although it presented some room for improvement. Although adaptive thresholds were individual values of each patient, therapists felt that the system should consider more information on the patient's condition (emotions, previous attempts, objectives) before making the decision to be or not more demanding. Patients were also asked about the usefulness of the feedback provided by the platform which responded affirmatively (3.89 ± 1.17). In the game of remembering the sequence of poses (Memory), they confessed to use visual feedback of eye color in many occasions to determine if they were close to the correct pose.

Table 5.23: Questions related to the factor of flexibility.

Q. ID	**Interview**	**Description**	**Mean**	**SD**
Q6	T. PS	Has the robot guided well to correct the children's postures?	4.06	0.83
Q6	T. PE	Was the robot able to adapt to the children's conditions?	3.25	0.77
Q16	P. PE	Have the robot's eye lights helped you while doing the exercises?	3.89	1.17

Robustness

Robustness is defined by USUS framework as *"the level of support provided to the user to enable a successful achievement of tasks and goals"* [Weiss et al. 2009]. For this study, this aspect refers to the capabilities of NAOTherapist to correct and prevent any patients' errors, and prolonged and consistent over time. The platform is designed to propose a set of pose-based activities helping patients with those that are incorrect. The key to success is to make the system robust for all poses, all patients and all possible situations.

Table 5.24 shows a summary of the results obtained through two questions in the post-evaluation phase. Therapists responded to whether the corrections made by the robot were accurate enough (T.PE.Q3). The result 3.06 ± 0.77 determined that yes, but experts said there were occasions and with certain poses that was not entirely accurate. The response of the patients was closely related and the result is consistent with the opinion of the therapists (P.PE.Q15). The patients averaged with 2.67 ± 1.22 that the robot sometimes asked them to repeat a pose that they considered they had done correctly. The level of demand of the robot has been questioned in previous evaluations, considering the platform as too demanding or "pick" when recognizing the poses. In most cases the errors occurred due to a problem of precision in the 3D-sensor recognition of the user's skeleton. Other times the system was too demanding with patients and made them repeat poses that could be correct from the point of view of the therapist. The robustness in the recognition and correction of poses could be the most criticized aspect of the system and with a major proposal for room for improvement.

Table 5.24: Questions related to the factor of robustness.

Q. ID	Interview	Description	Mean	SD
Q3	T. PE	Were the corrections of the robot accurate enough?	3.06	0.77
Q15	P. PE	Has the robot made you repeat a pose that you were doing well?	2.67	1.22

Utility

According to the USUS framework, the utility indicator is defined as *"the capability of the interface to be used to reach a certain goal or to perform a certain task"* [Weiss et al. 2009]. The utility of NAOTherapist has been evaluated in previous studies with great acceptance by experts, family members and patients. For the evaluation of this indicator in the HABIT camp, three questions were asked to therapists in post-session and post-evaluation phases.

After each session, the therapist in charge was asked whether the session had been useful for the patient (T.PS.Q12). According to the results of Table 5.25, the averaged value accumulated by all therapists is 4.10 ± 0.92, considering the experience useful for the patient. In the post-evaluation phase, two questions were formulated: whether the robot provided a positive therapeutic experience for the patient (T.PE.Q11) that obtained a 3.56 ± 1.03 and whether the robot was useful for therapeutic treatments (T.PE.Q12) whose average value was 3.31 ± 0.70. Both responses were very aligned, and although this result is lower than in post-session, most therapists accepted its use in pediatric therapy. Based on the observations, they saw a lot of potential to work cognitive aspects, attention and functional motor activities. Others believed that the tool had great diagnostic potential to measure the patient while performing therapy in a uninhibited and active way. The motivational incentive and its impact on patient therapy was an unanimous opinion among all experts.

Table 5.25: Questions related to the factor of utility.

Q. ID	Interview	Description	Mean	SD
Q12	T. PS	Has the session of today been useful for the rehabilitation of the child?	4.10	0.92
Q11	T. PE	Does the robot provide a positive therapeutic experience for children?	3.56	1.03
Q12	T. PE	Do you think the robot is useful for therapies with children?	3.31	0.70

5.4.4.2 Social Acceptance

Social acceptance of NAOTherapist is evaluated dealing with the second hypothesis: "H2: Is NAOTherapist accepted by the participants?". Although previous studies also took into account family members, in this study the participants refers to patients and therapists in charge. The USUS framework defines social acceptance as *"an individual's willingness based on interaction experiences to integrate a robot into an everyday social environment"* [Weiss et al. 2009]. The indicators that evaluate this factor applied to this study are: effort expectancy, attitude towards using technology, self efficacy, attachment and reciprocity. These indicators are derived from the UTAUT (Unified Theory of Acceptance and Use of Technology) model [Venkatesh et al. 2003].

Effort Expectancy

Effort expectancy is defined by the UTAUT model as *"the degree of ease associated with the use of the system"* [Venkatesh et al. 2003]. It refers to the degree of effort and difficulty involved in using or learning to use the NAOTherapist platform. This indicator was evaluated through two questions to therapists in the post-evaluation phase.

Table 5.26 summarizes the results to these two questions. In relation to the ease of deployment and operation of the robot (T.PE.Q16), most experts responded positively to this point (3.50 ± 0.52). The second question obtained 4.13 ± 0.72, considering the robot configuration task as a very simple task that was performed through a graphical interface. Based on the observations, therapists generally considered that the NAOTherapist platform was quite easy to deploy, operate and configure. The exercise configuration interface offered a simple and intuitive design. Although the results were very good, it is important to highlight the average age of the experts (25.6 years old) and the high experience in technology. It is true that none of them had worked with a robot, however, in the pre-study interviews (Pre-evaluation questionnaires) they recognized to use electronic devices (tablets, smartphones and computers) daily, and even some of them had involved video consoles and electronic games in their treatments. This previous experience is consistent with their perception of the effort expectancy.

Table 5.26: Questions related to the factor of effort expectancy.

Q. ID	**Interview**	**Description**	**Mean**	**SD**
Q16	T. PE	Do you think it is easy to deploy and operate the robot?	3.50	0.52
Q17	T. PE	And to configure it?	4.13	0.72

Attitude towards Using Technology

The attitude towards using technology is defined by the USUS framework as *"sum of all positive or negative feelings and attitudes about solving working tasks supported by a humanoid robot"* [Weiss et al. 2009]. During the pre-evaluation phase, patients were asked about their previous experience with technological devices. Most of them used a tablet (70 %), computer (40 %) or smartphone (50 %) almost daily. Everyone knew what a robot was. Although they had never interacted with one, they showed a very positive predisposition to do therapies with robots.

This indicator was evaluated in the post-session and post-evaluation phases. The therapists were asked about the attitude and predisposition of the patients during the sessions and the patients were asked after every session if they had been focused and had struggled to do the exercises.

Table 5.27 summarizes the responses of both collectives. Both therapists (T.PS.Q9 and T.PS.Q10) and patients (P.PS.Q4 and P.PS.Q5) shared that the latter had been engaged to the sessions and trained hard. The average values of the sessions were above 4 on the 5-point Likert scale. Additionally, the same question was asked to therapists in the post-evaluation phase (T.PE.Q8). The answer obtained 4.47 ± 0.72, considering that patients had a high commitment and motivation with the robot's activities.

Table 5.27: Questions related to the factor of attitude toward using technology.

Q. ID	**Interview**	**Description**	**Mean**	**SD**
Q9	T. PS	Have you seen the child engaged/committed to the session?	4.48	0.76
Q10	T. PS	Do you think the child has worked hard during the session?	4.28	0.81
Q8	T. PE	Were the children committed with the robot activities?	4.47	0.62
Q4	P. PS	Have you been attentive while playing with the robot?	4.73	0.55
Q5	P. PS	Have you tried hard in the exercises with the robot?	4.54	0.91

Self-Efficacy

The USUS framework defines self-efficacy as *"people's beliefs about their capabilities to produce designated levels of performance"* [Weiss et al. 2009]. To determine this indicator, patients evaluated their ability to fulfill the activities. The two fundamental tasks were typically: mimic the poses and remember sequence of poses.

According to the results of the Table, the patients were self-confident with the imitation part of the poses (3.11 ± 0.60). However, they acknowledged having more trouble remembering the sequence of poses in the Memory game.

Attachment

Attachment is defined by USUS framework as *"an affection-tie that one person forms between him/herself and another person or object - a tie that binds them together in*

Table 5.28: Questions related to the factor of self-efficacy.

Q. ID	Interview	Description	Mean	SD
Q20	P. PE	Did you find the poses easy to imitate?	3.11	0.60
Q21	P. PE	Did you find the poses easy to remember?	2.11	1.36

space and endures over time" [Weiss et al. 2009]. Attachment is one of the most important indicators in NAOTherapist. The bond or emotional ties between the robot and the patient usually originate naturally after prolonged exposure to the robot. There is a personification of the robot considering it as a social entity. The patient-robot bond favors adherence and the desire to continue working with it.

This indicator was evaluated by doing the post-session and post-evaluation questionnaires, see Table 5.29. After each session, patients were asked if they wanted to play again with the robot tomorrow (P.PS.Q8). The cumulative average obtained was 4.89 ± 0.42 of all sessions. This extraordinary result shows that the attachment of all patients was very high and that they always wanted to play with the robot again. In the post-evaluation phase, two questions were asked regarding this indicator: if they would like to continue doing therapy with the robot (P.PE.Q11) that obtained a 4.67 ± 0.71 and if they would like to have the robot at home (P.PE.Q12) whose average value was 4.33 ± 1.00. Both results were very positive in terms of attachment.

Table 5.29: Questions related to the factor of attachment.

Q. ID	Interview	Description	Mean	SD
Q8	P. PS	Would you like to play with the robot tomorrow?	4.89	0.42
Q11	P. PE	Would you like to continue doing therapy with the robot?	4.67	0.71
Q12	P. PE	Would you like to have this robot at home?	4.33	1.00

Two open questions were also raised regarding the name of the robot (P.PS.Q9). The objective was to determine the degree of personification perceived by the patient. Most of them chose names of other HABIT camp mates, family members or pets, which demonstrates a positive affective bond to the platform.

Reciprocity

Reciprocity is defined in the USUS framework as *"the principle of give-and-take in a relationship, but it can also mean the mutual exchange of performance and counter-performance. It is the positive or negative response of individuals towards actions of others"* [Weiss et al. 2009]. Reciprocity attempts to determine if the user perceives that the interaction with the robot is real and it is not a simple "machine" that collects the data, that is, there is a reciprocal two-way interaction channel between them.

To evaluate this indicator, patients were asked two questions in the post-evaluation phase: if the robot could see them (P.PE.Q5) and hear them (P.PE.Q6). According to Table 5.30, patients answered that the robot was able to see them (3.22 ± 1.64), although it was uncertain that it could hear them (2.67 ± 1.32). Unlike past studies, due to the overexposure of the platform in such a short period of time, some patients realized that the robot was actually "deaf". A fact that had not occurred until the camp, since that question was always scored better.

Table 5.30: Questions related to the factor of reciprocity.

Q. ID	Interview	Description	Mean	SD
Q5	P. PE	Did you have the impression that the robot was looking at you?	3.22	1.64
Q6	P. PE	Did you have the impression that the robot was listening to you?	2.67	1.32

Another perspective of reciprocity is to imagine what else the platform could provide us. They were asked to imagine what other things they would like to play with the robot. In general terms, patients responded: board games, sports, hide and seek, cards or dancing together.

5.4.4.3 User Experience

Evaluating the user experience with NAOTherapist deals with the third hypothesis: "H3. User Experience: Do participants have good experiences when interacting with NAOTherapist platform?". The USUS framework proposes a definition of this factor based on the Alben's general concept of user experience, and it refers to *"aspects of how people use an interactive product: the way it feels like in their hands, how well they understand how it works, how they feel about it while they are using it, how well it serves their purposes, and how well it fits into the entire context in which they are using* *it"* [Alben 1996]. The indicators that evaluate the user experience are: embodiment, emotion, human-oriented perception and feeling of security.

Embodiment

As defined in the USUS-framework, embodiment is described as *"the relationship between the robot and its environment"* [Weiss et al. 2009], the perceived impression not only of the physical aspect but also of the user's expectations. The evaluation of the embodiment in this study focuses on whether the patient's expectations in terms of enjoyment have been satisfied by the NAOTherapist platform.

In order to cross the results, the same patient-centered question was asked to therapists (acting as an observer) and patients (T.PS.Q8 and P.PS.Q7) after each session. Results can be followed in Table 5.31. Both perspectives agreed that patients enjoyed playing with the robot with values above 4.5 on average. In the post-evaluation phase, the same question obtains almost the same result (4.89 ± 0.33) as the accumulated post-session value. In view of the results, the system proves to have satisfied the patients' expectations with a new form of game-based therapy that was fun and enjoyable.

Table 5.31: Questions related to the factor of embodiment.

Q. ID	Interview	Description	Mean	SD
Q8	T. PS	Has the child enjoyed the session?	4.59	0.65
Q7	P. PS	Have you enjoyed playing with the robot?	4.83	0.41
Q24	P. PE		4.89	0.33

Embodiment is also defined as the user's perception from a more descriptive point of view. To assess how users saw the robot, in the post-evaluation phase, they were given a list of adjectives and asked to mark the five adjectives that best describe the platform. The results are shown in Figure 5.13. There are two categories: human-oriented and object-oriented adjectives. At first glance, it is observed that human-oriented were more frequently selected than object-oriented adjectives. In addition, positive adjectives were more selected in both categories, e.g. happy, beautiful, modern, easy, than negatives such as impatient, clueless, silly, resistant. This trend determines that patients saw the robot as a more human than artificial entity, attributing it to positive characteristics.

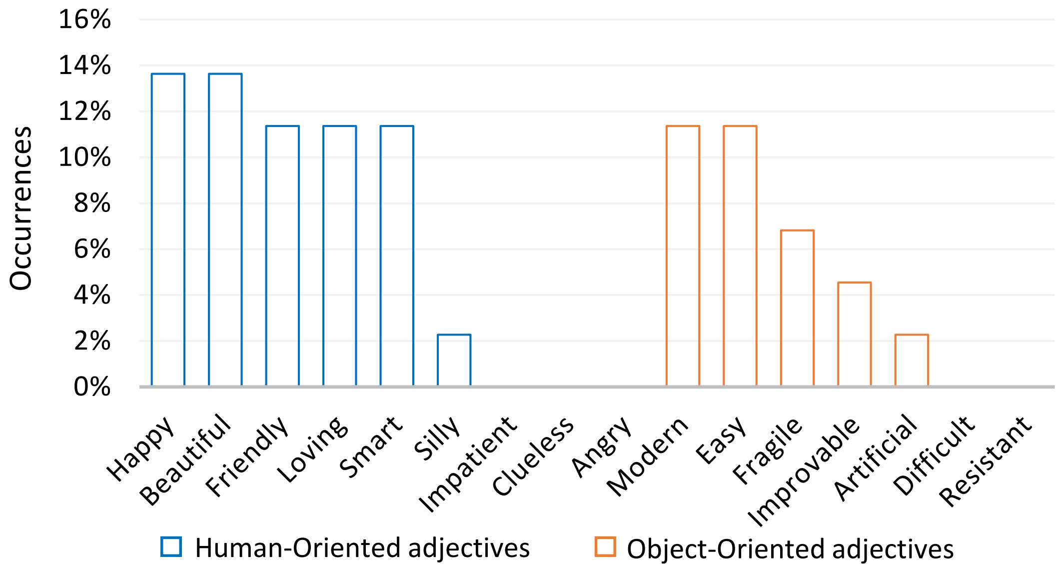


Figure 5.13: Frequency of selection of the adjectives proposed in the post-evaluation questionnaire.

Emotion

According to USUS framework, the emotion indicator *"implies that people tend to interact with computers and robots socially"* [Weiss et al. 2009]. Emotions is a fundamental aspect to evaluate in human-robot interaction processes and even more so when users are children. For this, a cross-assessment scheme was proposed: the patient evaluated his own emotions and the observer (therapist in this case) responded to the patient's perceived emotions. In this way, one could cross the results and draw interesting conclusions about personal and observed emotional perception. The emotions were evaluating using the SAM (Self-Assessment Manikin) scale on a five-point scale to assess for the valence, arousal and dominance [Geethanjali et al. 2017]. Figure 5.14 represents: A) emotional valence classifies positive and negative emotions - unhappy to happy, B) arousal assesses the level of excitement and alert - nervous to calm, C) dominance determines the control over the situation - submissive to dominant.

The evaluation of emotions was done in each post-session questionnaire by patients (P.PS.Q1) and therapists (T.PS.Q1). Table 5.32 presents a summary of the average

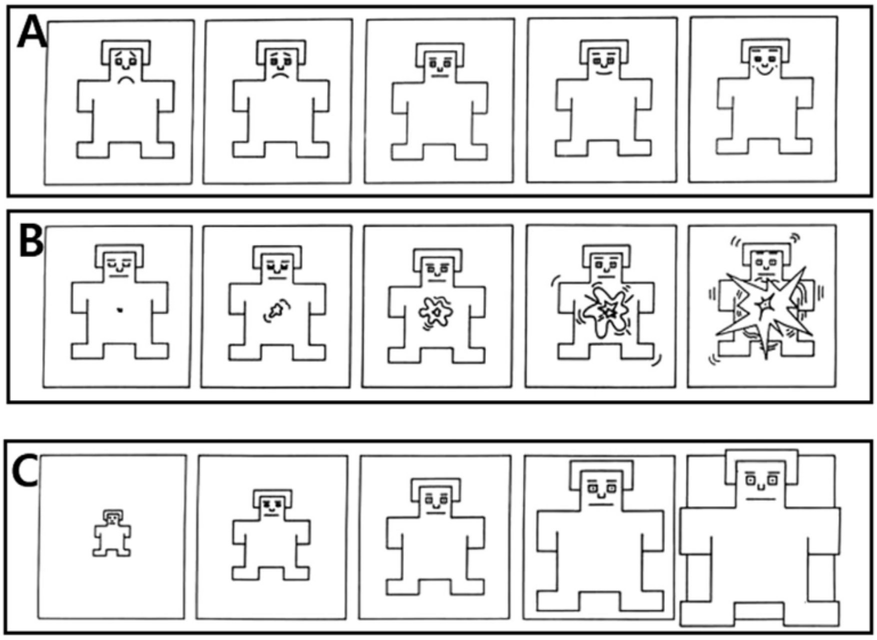


Figure 5.14: SAM (Self-Assessment Manikin) scale on a five-point scale to assess for the A) valence (unhappy to happy), B) arousal (nervous to calm) and C) dominance (submissive to dominant).

accumulated values and the std. deviation for the valence, arousal and dominance categories.

Table 5.32: Questions related to the factor of emotion.

Q. ID	Interview	Description	Mean	SD
Q1	T. PS	How do you think the child has felt with the robot?		
		Unhappy - Happy	4.75	0.55
		Nervous - Calm	2.48	1.48
		Submissive - Dominant	3.44	1.18
Q1	P. PS	How have you felt playing with the robot?		
		Unhappy - Happy	4.90	0.37
		Nervous - Calm	3.04	1.40
		Submissive - Dominant	4.19	0.98

More visually, these results are plotted as radar chart in Figure 5.15. In this graph the perception of the patient and that of the therapist are drawn. According to the results, the patients felt very happy, quite calm and with great control of the situation during the sessions. Therapists agreed on the positive valence and disagreed slightly on the arousal and dominance. The differences determine that the patients considered that they had more control and were calmer, and the therapists saw their patients more submissive and nervous. However, these differences are so small that it can be said that both perceptions were very aligned.

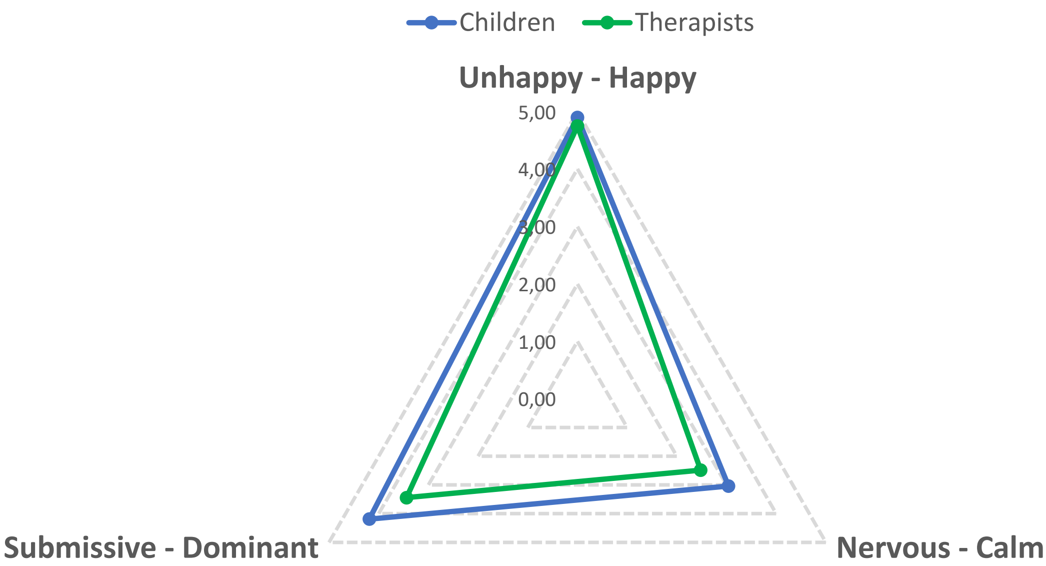


Figure 5.15: Difference in the perception of emotions between therapists and patients according to the SAM scale.

Human-Oriented Perception

Human-Oriented Perception is defined in the USUS framework as *"the capabilities of a social robot to simulate human perception"* [Weiss et al. 2009]. In relation to this indicator, the platform was evaluated in terms of how the movements are reproduced by both the patient and the robot. In addition to perceiving the user state, the system must also ensure that patients are able to reproduce the movements of the robot naturally.

The evaluation of this point focuses on how the therapist perceives the movements reproduced by the patients after each session (T.PS.Q5) and the naturalness of the robot movements (T.PE.Q7). Table 5.33 shows the results of the first question, which obtains a cumulative average value of 4.05 $\pm$ 0.67 of all sessions. This means that most therapists considered that, despite doing an imitation exercise with a robot, the patient managed to reproduce it naturally. The second response was related to the movements of the robot that obtained an average rating of 3.31 ± 0.87. Some therapists commented that the NAO platform presented certain physical design restrictions, and therefore limited their movements, e.g. elbow flexion less than 90º, moving fingers, etc.

Table 5.33: Questions related to the factor of human-oriented perception.

Q. ID	Interview	Description	Mean	SD
Q5	T. PS	Has the child reproduced the movements naturally?	4.05	0.67
Q7	T. PE	Were the movements of the robot natural?	3.31	0.87

Feeling of Security

Feeling of security is considered a key aspect in human-robot interaction. *"As soon as humans collaborate together with robots in the same environment, safety and security issues arise"* [Dautenhahn et al. 2006]. One of the keys for patients to feel safe with the robot is to offer an interaction at a social distance that does not threaten their personal space. In all sessions with NAOTherapist, the patient was always at least one and a half meters away from the robot that remained in the same position throughout the session. In addition, the height of an NAO robot is 0.5 meters, so at the end any patient felt insecure when interacting with the platform.

However, there are other aspects regarding the feeling of security that were evaluated. The sessions consisted of a set of physical rehabilitation activities, and the robot offered the necessary feedback so that the patient could perform them correctly. It was interesting to determine if the flow of interaction could overwhelm or stress patients generating some kind of insecurity. Table 5.34 summarizes the results to the questions proposed to therapists (T.PE.Q5) and patients (P.PE.Q13 / Q19) in the post-evaluation phase. The results suggest that patients had barely felt overwhelmed during the sessions with the robot (3.75 ± 0.71), this statement was also shared by the therapists (3.62 ± 0.50). Nor they perceived that the platform had scolded them in achieving the exercises (3.78 ± 0.67), so that the feeling of security was maintained during the study.

A particular case was that of patient P04 who in the first sessions was afraid of the robot. However, after a few sessions this feeling disappeared being one of the cases

Table 5.34: Questions related to the factor of feeling of security.

Q. ID	Interview	Description	Mean	SD
Q5	T. PE	Were the children overwhelmed by the robot during the sessions?	3.62	0.50
Q13	P. PE	Do you think the robot scolded you while you played?	3.78	0.67
Q19	P. PE	Has the behavior of the robot overwhelmed you?	3.75	0.71

that more emotional ties forged with it. In the last sessions, this patient was willing to touch him and sit with him. The conclusion reached is that for some participants it was necessary to make a previous introduction to the robot so that they knew it before starting to play with it.

5.4.4.4 Societal Impact

Societal Impact of NAOTherapist is evaluated dealing with the fourth hypothesis: "H4. Social Impact: Is the impact of NAOTherapist in the society positive?". The USUS framework defines societal impact as *"every effect of an activity on the social life of a community in general and more specific for the proposed framwework"* [Weiss et al. 2009]. This factor describes future assumptions about the impact that the robotic platform would have on society and its influence on neurorehabilitation treatments. The indicators that evaluate this factor and that have been applied to this study are: quality of life and working conditions.

Quality of Life

Within the USUS framework, Quality of Life indicator is focused on *"the integration of intelligent robotic technology into everyday life"* [Weiss et al. 2009]. This indicator was evaluated through interviews and open questions to therapists in the post-evaluation phase. In general terms, therapists valued the potential of the tool and the impact on the patient's quality of life. The motivational incentive of the platform could strengthen adherence to treatment, so that patients arrived more excited at the clinic.

In line with the above, two questions were raised to the therapists: The first, *T.PE.Q13: What contribution does the robot make that a human therapist does not get?*. Most of the responses recognized the improvement in motivation and concentration of the patient. They all stated that the game-like activities with the platform aroused their imagination and managed to keep their attention for longer. Under the patient's perspective, the robot was an innovative element that added value to the HABIT camp. The second question to therapists was *T.PE.Q21: Have you seen improvement in the patient by the use of the platform?*. As previously mentioned, 70% of therapists stated that their patients had improved when using of the platform. The majority of the responses focused on a functional improvement. In general, most of patients failed less and achieved better results with the robot postures, and recognized an improvement in attention, concentration and motivation. For all of therapists, it was a pleasure to see how patients enjoyed the rewards/dances, their faces of surprise and their conversations towards the robot room about what would be today's game with NAO.

Working Conditions

According to the USUS framework, working conditions indicator *"includes all aspects affecting how people carry out their job and how employers take care of their employees, including things like working contracts, wages, working times and work organization"*[Weiss et al. 2009]. To assess this indicator, several questions were raised to therapists in the post-evaluation phase. The idea was to determine if they would be interested in having this platform in their clinic and what impact it could have on their work.

Regarding this indicator, therapists responded if patients work with the robot as in conventional therapy. Table 5.35 shows the results to this question. Both in the post-sessions phase and in the post-evaluation phase, the responses were very aligned. Therapists believe that in conventional therapy they get the patient to work in similar conditions. They must strive to maintain the motivation and engagement throughout the session. On the other hand, they admitted that the platform could provide them with great help in this regard.

Table 5.35: Questions related to the factor of working conditions.

Q. ID	Interview	Description	Mean	SD
Q11	T. PS	Do you think the children will work the same with conventional therapy?	3.72	0.88
Q9	T. PE		3.19	1.05

A key question was *T.PE.Q14: Would you like to have this robot in your rehabilitation center?*, 80% of the therapists were interested in using NAOTherapist in their rehabilitation sessions, the remaining 20% considered that some issues should be improved before involving it in their therapies. They were also asked about potential uses: *T.PE.Q15: How would you use the robot in your therapies?*. Most of the responses proposed its use as a tool to improve adherence to treatment that could diversify the activities of a session. Using it as an incentive or reward after the session was also discussed. Other therapists saw great potential in automatic patient measurement compared to manual measurement methods. In goniometry, the measurements are dependent on the expert who takes them, among experts, different results are usually obtained. Therapists considered that capturing the patient's mobility ranges while interacting with the robot could save time, ensuring the reliability of the data.

The last part of the interview focused on the perception of the tool as threat in their work. Therapists were asked: *T.PE.Q18: Do you think this robot could replace a therapist?*. 100% of therapists responded that the tool could not replace them in their workplace since their presence was necessary to configure and monitor the session. NAOTherapist was always perceived by the therapist as a tool to support and monitor the treatment.

5.4.5 Discussion

The NAOTherapist platform was evaluated at the HABIT intensive therapy camp for patients with cerebral palsy. Among the participants, there were 10 patients between 6 and 12 years old and 14 clinical professionals (occupational therapists, physiotherapists, psychologists and physical educators). NAOTherapist participated for 11 consecutive daily sessions offering game-like activities to patients. A total of 110 sessions were carried out without any incident. The therapists assigned to each patient were responsible for configuring and adapting the session to the patient. From there, the platform ran autonomously.

The clinical study focused on evaluating the four factors within the USUS framework (utility, social acceptance, user experience and societal impact) through interviews, questionnaires and objective data collected by the system. Three evaluation phases were distinguished: pre-test, post-session and post-evaluation. More than 220 patient and clinical professionals questionnaires were administered and analyzed. More than 3 hours of motion perception data per each patient were also collected.

In summary, Figure 5.16 shows the average score obtained from 0 to 5 of the USUS factors and the key indicators. The overall results are very promising: 3.8 in usability, 3.7 in social acceptance, 4.1 in user experience and 4.0 in societal impact. In detail, we can see that there are indicators that have room for improvement. For example, the robustness indicator obtained a 2.9 fundamentally due to the lack of precision in the robot corrections and a 2.6 self-efficacy, since it was difficult for patients to remember the poses in the Memory game. In addition to trying to improve these two aspects, therapists expressed the need to continue improving the patient's adaptive abilities from the feedback offered to the degree of personalization and configuration of the therapy (flexibility 3.7). This need was taken into account for the following studies.

According to the observations, NAOTherapist was able to offer a fluent cHRI (efficiency 4.1) with an easy-to-follow methodology for the patient (learnability 4.1). Patients reproduced naturally the robot movements (human-oriented percepction 3.7). 90% of the patients improved in the use of the platform by reducing their thresholds in most of the poses of the affected arm (effectiveness 4.5). The tool was seen as an added value in neurorehabilitation sessions as an incentive and improvement in adherence to treatment (utility 3.7 and attitude towards using technology 4.5). Therapists were able to easily operate and configure the tool (effort expectancy 3.8). Patients demonstrated that sessions were very good due to the strong positive affective bond with the robot (attachment 4.7). They had the impression that they were interacting with a real interactive agent (reciprocity 3.0), although some of the patients realized that the robot could not hear them. The emotional valence obtained was very positive, they felt happy, calm and dominant throughout the study (emotion 4.0). Patients did not see the robot as a threat, although the level of demand could frustrate them at some point (feeling of security 3.7). In general terms, therapists saw the potential of the tool and the positive impact on the patient's quality of life (quality of life 4.1). The motivational incentive of the platform could strengthen adherence to treatment, so that patients arrived more excited at the clinic. 80% of the therapists were interested in using the current NAOTherapist prototype and the remaining 20% after some improvements (working conditions 3.9). The tool would allow them to diversify the activities of a session. Using it as an incentive or reward after the session was also discussed. Other therapists saw great potential in capturing the patient's mobility ranges while interacting with the robot, saving time while ensuring the reliability of the data.

Figure 5.16: Summary of evaluation factors in the HABIT study.

5.5 Conclusion

An autonomous social robotic prototype called NAOTherapist was designed to carry out hands-off neurorehabilitation sessions based on upper-limb gamified activities. This tool has an expert-friendly design to provide health professionals the opportunity to adapt each treatment to every patient. The system incorporates positive reinforcements that motivate and guide the patients during their treatment, improving the adherence of these to the therapy. This robotic technology has been validated in the rehabilitation of pediatric patients with motor needs compared to conventional treatments, providing very promising results.

The platform was involved in three different evaluation scenarios: first contact, long-term adherence and intensive therapy. In the first contact phase, 117 typically developing children interacted with the earliest prototype in a unique session. The main objective was to determine whether the cHRI provided by the platform was good enough to carry out the sessions. To date, this is the largest evaluation in the literature of SAR in pediatrics for motor rehabilitation. The lesson learned in this first iteration was that "*sometimes less is more*", that is, given the possibility of including a multi-modal perception system to offer a more complex cHRI (voice recognition, emotions, etc.), an more simple approach was chosen guaranteeing a fluid, safe and efficient interaction. In the same phase, a pilot study was conducted with 3 patients of the Virgen del Rocío University Hospital (VRUH) where the platform demonstrated to be very promising and useful in therapy. In these first sessions with patients, the need to integrate mechanisms of adaptation and customization of therapies was detected, with the motto "*every patient is a world*".

In the second episode, the platform was deployed in the VRUH for a long-term adherence study. For 4 months, 9 patients with obstetric brachial plexus palsy and cerebral palsy had weekly rehabilitation sessions, the first two months with traditional therapy and the second two with NAOTherapist. According to clinical measures, patients presented a slight improvement in their motor skills after this study. This was especially evident in those patients who attended all scheduled sessions. Relatives in general considered patients to be more motivated to attend the hospital when having sessions with the robot. Although the level of adherence was acceptably good, this evaluation compromised "*the novelty effect of the platform*", that is, patients lost interest in the platform as time passed.

In the third episode, NAOTherapist participated in an intensive therapy camp with 10 patients with cerebral palsy with daily sessions for 11 days. The system was highly improved since it would be evaluated in an environment of maximum demand. When having daily sessions, patients had to be engaged throughout the study. Game mechanics were included as narrative immersion and new game-like activities. 110 clinical sessions and more than 220 questionnaires were administered and analyzed. Objective perception data demonstrated that 90% of patients improved in the robotic activities. In summary, the results of the USUS factors and key indicators were very promising (3.8 in usability, 3.7 in social acceptance, 4.1 in user experience and 4.0 in societal impact, in a 1-5 scale). The lesson learned was that "*every effort has its rewards*", since gamification mechanics had managed to maintain patient adherence throughout the study with significant results. However, therapists also expressed the need to continue improving the patient's adaptive abilities from the feedback offered to the degree of personalization of the therapy. This need was taken into account for the following studies.

Each of these evaluations allowed the platform to evolve, incorporating functionalities and detecting new future needs. In total, 244 different children (21 of them pediatric patients) interacted with NAOTherapist in a total of 429 sessions executed without significant incidences. Of these 429 sessions, 206 were in clinical settings. Regarding to the rest of the stakeholders, 11 relatives and 20 clinical experts were consulted through interviews and questionnaires. Despite these extensive evaluations, there is still much work to do to achieve the ultimate intended goal: "*the incorporation of technologies, such as NAOTherapist, in routine therapeutic procedures*". Although these studies offer an initial experience from different scenarios in the search of new requirements, the results presented here help to establish a solid base to extend this line of research aiming at offering novel tools to healthcare professionals.

Chapter 6

Infant-Robot Interaction Study for Motion Encouragement

This study tries to cover one of the main needs of the NAOTherapist prototype. The user adaptation system described in Chapter 4 and evaluated in Chapter 5, presented an approach with a high level of customization: each patient had a value per arm, pose and joint, but with great room for improvement. The problem lies in the decision to increase or reduce the threshold, giving more or less difficulty to the activity. This decision is made based on a set of fixed rules based on whether the patient does it right or wrong. However, this approach is rigid and is not general to any user, as the rules to change the difficulty are not always known.

For this reason, this chapter proposes an early approach based on Reinforcement Learning (RL) to improve the adaptation system in a different use case of NAOTherapist. So, in addition to discover new approaches to adapt the patient's difficulty, this would allow to validate the SAR-based framework in other scenarios. This work was done during a four-month stay at the University of Southern California, at the Interaction Lab of Maja Matarić, in collaboration with Beth A. Smith from the USC Division of Biokinesiology and Physical Therapy.

This chapter is structured as follows: Section 6.1 explains the background of this study. Then, Section 6.2 presents the main objectives the Infant-Robot contingency study. Next, Section 6.3 explains the origin of the infants' data from the first part of the contingency study [Fitter et al. 2019], summarizing the foundational study that was carried out. From the principles of the R^3 cHRI model (Figure 3.3), Section 6.4 provides the proposed model from the second part of the contingency study, from the discretization to build the set of thresholds to the RL-based approach. It also describes the robotic software architecture built from the proposed general framework for hands-off robotics rehabilitation (Figure 3.4). Section 6.5 presents the experimental model and results of 4 infants. Finally, Section 6.6 summarizes the work and outlines next steps of this research.

6.1 Background

Infants produce a variety of movements in order to modulate task-specific actions such as reaching, crawling, and walking [Gibson et al. 2000, Thelen et al. 1994]. Through a dynamic process of exploration and discovery, they learn how to control their bodies and interact with their environments. In contrast to typically developing (TD) infants, infants at risk (AR) for developmental delays often have neuromotor impairments involving strength, proprioception, and coordination. These challenges can lead to greater difficulty with movement and potentially a decreased motivation to move and explore.

Motor exploration and the practice of motions are essential facets of infant development. Learning to perform actions from grasping a favorite toy to kicking with knee extension have a substantial impact on infant cognitive and motor development. Some infants, especially those at risk for developmental delays, move an insufficient amount or practice non-optimal movement patterns. This tendency can lead to inadequate development of age-appropriate strength, proprioception, and coordination. A recent estimate determined that approximately 9% of infants born in the United States are at-risk and could benefit from early targeted interventions [Rosenberg et al. 2013].

Past works have used wearable sensors and/or 3-dimensional motion analysis systems to assess differences in movement patterns between infants with TD and infants AR or with developmental delays. Studies have demonstrated that movement variables such as kicking frequency, spatiotemporal organization, and interjoint and interlimb coordination are different between infants with TD and infants AR [Smith et al. 2017], with intellectual disability [Kouwaki et al. 2014], with myelomeningocele [Rademacher et al. 2008, Smith et al. 2008], with Down syndrome [McKay et al. 2006], or born preterm [Geerdink et al. 1996]. Studies have also shown that the acquisition of new motor skills is correlated to subsequent cognitive development in infancy [Kermoian et al. 1998, Oudgenoeg-Paz et al. 1998], thus interventions to promote motor skills have the potential to be used to enhance the overall infant development.

In order to achieve this motor skills promotion, a personalized contingency feedback adaptation system is developed and evaluated to encourage infants aged 6 to 8 months to gradually increase the peak acceleration of their leg movements. The ultimate challenge is to determine if a socially assistive humanoid robot can guide infant learning using contingent rewards, where the reward threshold is personalized for each infant using a RL algorithm.

6.2 Objectives

In the first part of this contingency study, the goal was for infants to discover and learn that the movements of a humanoid robot are contingent upon their movement [Fitter et al. 2019]. The robot performed a reward action (kicking a ball on a string) contingently, in response to a desired movement by the infant. Specifically, the robot rewarded the infant when s/he produced a leg movement above a specified, constant acceleration value, which we call the activation threshold. In the second part of this contingency study, we created a personalized contingency feedback adaption system that aims to encourage infants to gradually increase their peak acceleration of each movement [Pulido et al. 2018].

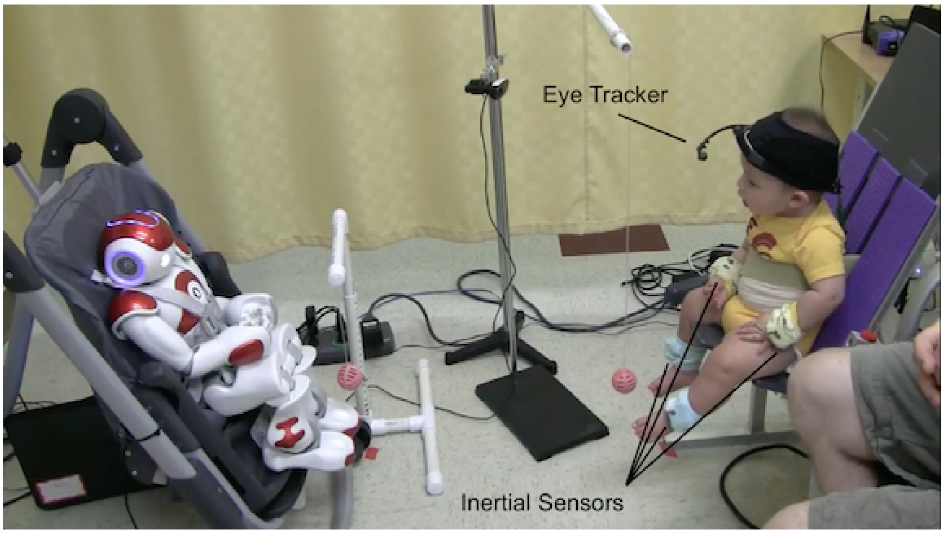
This work focuses on the evaluation of a RL algorithm that moderates the adaptation of the activation threshold using the data distributions of the acceleration peaks of every infant from the first part of the contingency study. The experimentation presented as follows uses those data as input for the model, to generate activation threshold values that adjust to each distribution individually.

6.3 Model Training Data

The training data used in this work were collected in the first study [Fitter et al. 2019]. We summarize the data collection only briefly here.

Eight infants with TD between the ages of 6 and 8 months participated in a contingency feedback experiment in the Greater Los Angeles area. Only TD infants were recruited for this study as the first step was to enable the system to adapt to typical infant exploratory movement behavior.

The infant was placed in front of a NAO robot in a chair that allowed for full leg mobility, as shown in Figure 6.1. The infant wore a head-mounted eye tracker. Opal inertial movement sensors [APDM Wearable Technologies, Portland, OR, USA



Published in [Fitter et al. 2019]

Figure 6.1: An infant study participant interacting with the NAO robot in the first study.

2018] were affixed to each infant limb using cuffs with pockets. The sensors tracked the tri-axial acceleration and angular velocity of each limb.

For two minutes, the infant's baseline movement was measured. During that time, the robot remained inactive. After the baseline, the robot demonstrated the reward action three times. The action was a basic knee flexion kick at a ball on a string. After the demo, the contingency phase of the study ran for eight minutes. If the infant produced an acceleration from the right leg above a fixed threshold of 3.0 $\mathrm{m\,s^{-2}}$, the robot performed the reward action. We chose the acceleration threshold based on a previous study that measured the accelerations of infant leg movements [Trujillo-Priego et al. 2017]. In this study, the difficulty of the activity did not change and the threshold remained fixed throughout the session. The study was approved by the University of Southern California Institutional Review Board under protocol #HS–14–00911.

Table 6.1 shows the acceleration peaks from the eight infants in the study. The variance among the participants is notable. The values of the means vary based on performance during the session. For instance, infant 1's mean peak acceleration is twice that of infant 5. Likewise, the maximum acceleration values reached by each infant and the number of acceleration peaks generated have a large variance. This is an indication that there is great heterogeneity in the participant pool, supporting personalized models rather than a generalized approach.

VARIABLE	N	MEAN	STDEV	MIN	Q1	MEDIAN	Q3	MAX
ACC_PEAKS_U01	655	11.20	9.65	3.00	4.98	8.53	13.77	87.39
ACC_PEAKS_U02	417	9.77	8.06	3.01	4.30	6.31	12.51	45.66
ACC_PEAKS_U03	166	6.63	7.01	3.00	3.47	4.57	7.056	55.74
ACC_PEAKS_U04	326	9.51	8.61	3.02	4.21	5.87	11.15	63.49
ACC_PEAKS_U05	311	5.95	4.20	3.00	3.60	4.38	6.44	38.11
ACC_PEAKS_U06	499	8.98	8.69	3.00	4.20	5.78	9.38	72.41
ACC_PEAKS_U07	273	18.56	22.72	3.01	4.12	6.53	24.46	94.92
ACC_PEAKS_U08	359	7.11	6.16	3.01	3.85	4.98	7.88	48.26

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Table 6.1: Statistical outcomes of the study participants; N is the number of detected acceleration peaks for each participant.

The results of the previous study were promising and informed the objectives of this work. The majority of infants were able to learn the contingency with a set activation threshold. They moved above threshold more often in the contingency phase, in which they interacted with the robot, than in the baseline phase. Therefore, the next step is to try adjust the difficulty of the activity and determine if infants are able to adapt to a changing activation threshold.

6.4 RL Adaptation Model

In order to personalize the demanding level of the activity, different levels of difficulty are established and the participant starts at a low level. Difficulty levels are related to thresholds of acceleration peaks. The learning model must find the policy that allows to move between the different levels from the participant's progress while maximizing the received reward (average acceleration). The idea is to adjust the specificity of the learning task – creating movements with higher acceleration – by adapting the acceleration threshold required to receive the contingency reward based on the infant's past performance on the task.

Prior to this, Section 6.4.1 offers background on how a task is modeled in reinforcement learning. Next, Section 6.4.2 presents the model designed to solve the adaptation of babies' difficulties in the contingency study.

6.4.1 Background on RL

A RL environment is typically formalized by means of a Markov Decision Process (MDP) [Sutton et al. 1998]. A MDP consists of a set of states S, a set of actions A available from each state, the reward function $R : S \times A \rightarrow \Re$ which assigns numerical rewards to transitions, and transition probabilities $T : S \times A \times S \rightarrow [0, 1]$ that capture the dynamics of a system. The goal is to learn a policy π, which maps each state to an action, such that the return $J(\pi)$ is maximized:

$$J(\pi) = \sum_{k=0}^{K} \gamma^k r_k \tag{6.1}$$

where r_k is the immediate reward received in step k, and γ is the discount factor which conholds how much the future reward is taken into account (with $0 \leq \gamma \leq 1$). We assume that the interaction between the learning agent and the environment is divided into episodes, where K is a time instant at which a terminal state is reached, or a fixed length for a finite horizon problem. Traditional methods in RL, such as TD-learning [Sutton et al. 1998], typically try to estimate the return (sum of rewards) for each state s when a particular policy π is being performed. This is also called the value-function $V^\pi(s) = E[J(\pi)|s_0 = s]$.

The value of performing an action a in a state s under policy π is represented as $Q^\pi(s, a) = E[J(\pi)|s_0 = s, a_0 = a]$. This value represents the estimated return, i.e. sum of rewards, the system will receive when it performs action a in the state s, and follows the policy π thereafter. The Q-function is also called the action-value function. The Q-learning algorithm [Watkins 1989] is one of the most widely used for computing the action-value function. Given any experience tuple of the type $< s, a, s', r >$ - where s is a state, a is an action, s' is the state achieved when executing a from s, and r is the immediate reward - it updates the Q-function following Equation 6.2.

$$Q^\pi(s, a) \leftarrow Q^\pi(s, a) + \alpha(r + \gamma \max_{a'} Q^\pi(s', a') - Q^\pi(s, a)) \tag{6.2}$$

where γ is the discount factor, and α is a learning rate. To correctly approximate the Q-function, the Q-learning algorithm uses an exploration strategy (e.g., ϵ-greedy, softmax) as a balance between the exploration of random unexplored actions and the exploitation of the ongoing learned policy [Tijsma et al. 2016]. In domains with a discrete state-action space it is usual to use a tabular representation of the Q-function.

Such Q-tables have as many rows as states existing in the domain, and as many columns as actions that can be executed in each of these states. Each of the positions in the Q-table is the value of the Q-function for the corresponding state and action.

6.4.2 User Adaptation Model

This section explains the proposed model for threshold adaptation in the infant movement contingency study. Section 6.4.2 provides a high level description of the problem. Section 6.4.2 explains the discretization of the peak acceleration values. Finally, Section 6.4.2 presents the RL approach for the adjustment of difficulty.

Problem Description

As noted earlier, the objective of the model is to adapt the activation threshold θ of the robot's reward action in real time. To achieve this, the contingency phase was segmented and the participant's progress evaluated to determine the threshold for the next segment. Progress is defined in terms of the average of the acceleration peaks, since this work is focused on identifying thresholds that achieve a higher average in the acceleration of the infant's movements.

The threshold adaptation process was carried out during the contingency phase, in which the robot gave a reward (i.e., kicking the ball) each time the infant exceeded the current threshold, otherwise the robot remained still. Figure 6.2 is a representation of the contingency timeline divided into N segments. Each segment lasts 40 seconds; the duration was determined empirically to allow enough time for the infants to adapt to the new difficulty and for the model to receive enough learning experiences in every session.

The system started with an initial threshold θ^0 that changed over time based on the outcome obtained in each segment. At each time step n with $0 < n < N$, the model decides whether to raise, lower, or keep the threshold value θ^n, i.e., the difficulty of the activity (assuming higher thresholds are more difficult), based on the average value of the acceleration peaks obtained in the last segment. Each θ^n took its values from a set of thresholds Γ selected as described in Section 6.4.2.

The objective was to find the value of the threshold θ that maximized the acceleration of each infant's target limb. As shown in Section 6.3, the acceleration values reached by the infants are quite different from each other. Therefore, it is important

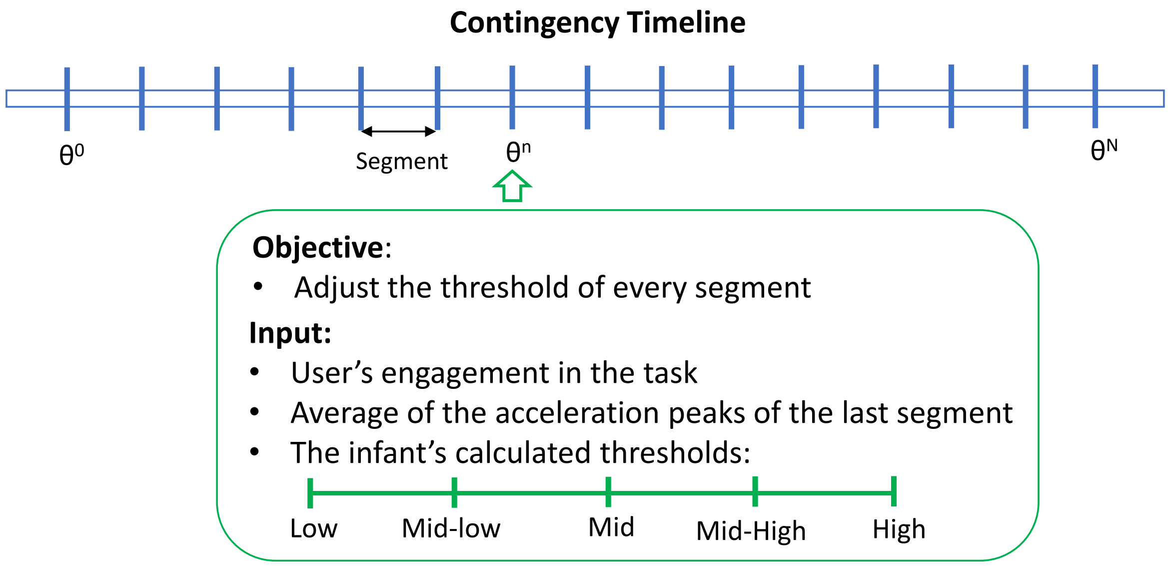

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Figure 6.2: Representation of the contingency problem.

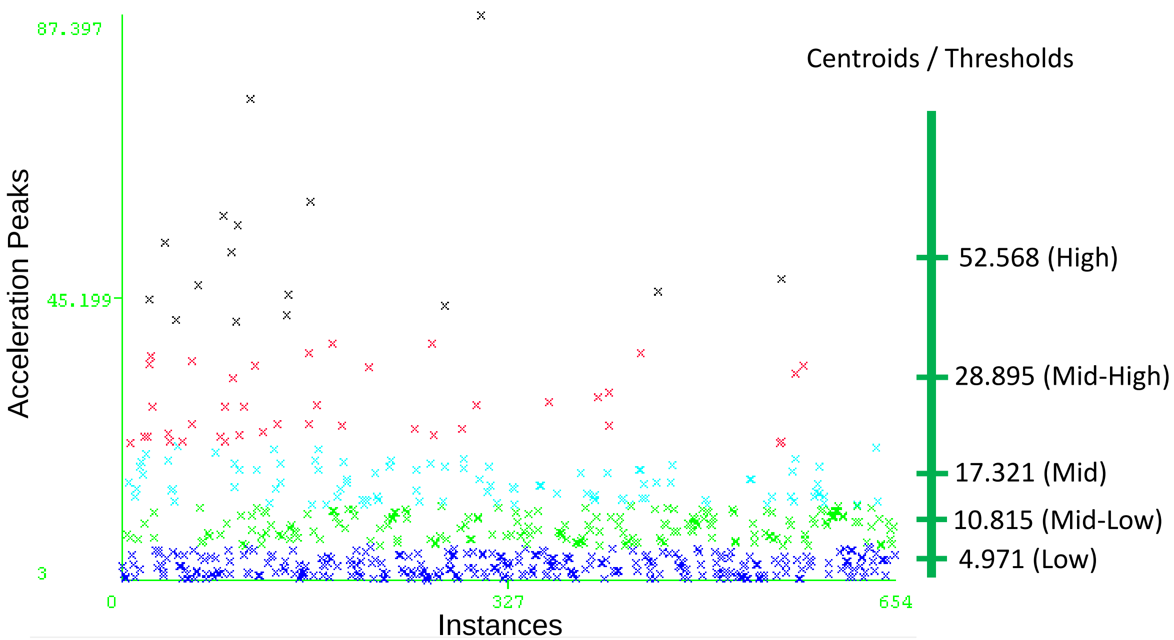
to learn an individual model of each infant in order to obtain the threshold. The decision to modify the threshold is dependent on the threshold levels for each infant, the average acceleration value obtained in the previous segment, and the infant's degree of engagement. These variables were chosen because they are used by experts, and the aim is to learn a policy for each infant that adjusts the level of difficulty of the activity similar to the way a health care professional would.

Discretization of the Acceleration Values

This section explains how the acceleration values of each infant were discretized to built a set $\Gamma = \{\theta_1, \theta_2, \ldots, \theta_q\}$ composed of q discretized threshold values that best match the data collected in their past sessions. In this study, 5 levels of difficulty related to acceleration peaks were established a priori, i.e., $q = 5$. Additionally, we assumed Γ is sorted in ascending order, i.e., $\forall i, j \; and \; i < j, \; \theta_i < \theta_j$ so that each threshold value corresponded to a level of difficulty: "low, mid–low, mid, mid–high, high".

As discussed in Section 6.3, preliminary analysis of the data revealed large differences in the movement data captured from the participating infants; some demonstrated double the average acceleration peaks of others. This evidence is consistent with previous research in development [Adolph et al. 2011]. Together with potentially higher variability within and across infants in different AR populations, this determined the need to create independent models for each participant. This, in turn, suggested that each infant should have a discretized set of thresholds, Γ, adapted to their abilities.

Instead of using a uniform discretization, we used a *K-means* algorithm with $k = 5$ that allowed for finding the five centroids that best separated the acceleration data for each infant [Hartigan et al. 1979]. The centroids were directly related to the five levels of difficulty of the problem. Therefore, each threshold value $\theta_i \in \Gamma$ corresponded to a different centroid. Figure 6.3 shows an example for the data gathered from infant 1. The graph is the representation of the allocation of the instances to the different clusters found by the algorithm (the blue points corresponds to the instances in cluster 1, the green points to the instances in cluster 2, and so on). Furthermore, each cluster is represented by a centroid that corresponds to a value associated with the level of difficulty (in this case, $\Gamma = \{4.97, 10.81, 17.32, 28.89, 52.56\}$). In this example, and in most of the participants, there is no homogeneous allocation of the instances in the clusters due to the way in which the data are distributed: 47 % (low), 29 % (mid–low), 15 % (mid), 6 % (mid–high), 2 % (high) for the infant 1. This means that most instances are concentrated around low levels of acceleration, since infants reach the highest peaks of acceleration at specific times.



Published in [Pulido et al. 2018]

Figure 6.3: Estimation of thresholds of the infant 1 using K-Means for the discretization of the accelerations peaks.

Mapping the Threshold Adaptation Problem onto Reinforcement Learning

In this section, we describe the mapping of the problem of threshold adaptation of an infant described in Section 6.4.2 onto an RL approach. Such modeling requires defining all the elements of a MDP: the state and action spaces and the reward and the transition functions [Sutton et al. 1998]. We consider this to be an episodic task, where for each episode the infant is evaluated in N steps.

In this work, a state $s \in S$ is a tuple in the form $s =< \xi, \theta >$, where ξ and θ are respectively the disengagement of the infant and the current threshold. Feature ξ is a binary feature, i.e., $\xi \in \{0, 1\}$, where $\xi = 0$ if the infant is engaged, and $\xi = 1$ otherwise. Instead, feature θ takes values from the discrete set $\Gamma = \{\theta_1, \theta_2, \ldots, \theta_q\}$ built by discretizing the acceleration values of each infant, as described in Section 6.4.2. Therefore, the size of the state space S is $2 \times q$.

We consider the action space A as being composed of three actions, $A = \{-1, 0, 1\}$. These actions are used to decrease, leave as is, or increase, respectively, the threshold θ of the current state.

After performing an action a^n in state s^n, where $n =< g^n, \theta^n >$, the agent transits to a new state $s^{n+1} =< \xi^{n+1}, \theta^{n+1} >$. A transition function is required to compute the values for ξ^{n+1} and θ^{n+1}. The value of ξ^{n+1} is computed using Equation 6.3:

$$\xi^{n+1} = \begin{cases} 1, & \text{if } countHits < 2. \\ 0, & \text{otherwise.} \end{cases} \tag{6.3}$$

where $countHits$ is the number of times the infant moves with an acceleration above or below threshold θ^n in step n. To compute the value of θ^{n+1}, we assume that $\theta^n = \theta_i$, i.e, θ^n at step n corresponds with the i-th threshold in Γ. Then, we compute θ^{n+1} as in Equation 6.4.

$$\theta^{n+1} = \theta_{i+a^n} \tag{6.4}$$

Therefore, if $a^n = 1$, the threshold is increased and θ^{n+1} takes the value of the $(i+1)$-th element in the Γ set, i.e., $\theta^{n+1} = \theta_{i+1}$. Conversely, if $a^n = -1$, the threshold is decremented and takes the value of the $(i-1)$-th element, i.e., $\theta^{n+1} = \theta_{i-1}$. If it is unchanged, then $\theta^{n+1} = \theta_i$.

Finally, when the learning agent performs an action a^n in a state s^n and moves to a state s^{n+1}, it also receives a reward signal r^n. We formulate the reward function as shown in Equation 6.5.

$$r^n = \begin{cases} 0, & \text{if } countHits = 0. \\ avgSuccAcc \times (countSuccHits/countHits), & \text{otherwise.} \end{cases} \tag{6.5}$$

where $avgSuccAcc$ is the average acceleration of the infant's movements above threshold θ^n, $countSuccHits$ is the number of times the infant moves with an acceleration above the threshold θ^n, and $countHits$ is the number of times the infant moves (above or under the threshold θ^n). The rationale behind the reward function in Equation 6.5 is as follows. If the infant does not move, the reward received is 0. If the infant moves ($countHits > 0$), and the threshold θ^n is exceeded ($countSuccessHits > 0$), the reward is greater than 0. If the threshold is easily exceeded by the infant, the reward is expected to be higher, consistent with a higher threshold. Conversely, if the threshold is not easily exceeded by the infant, the reward decreases, since $countSuccessHits$ tends to 0.

Finally, the reward function in Equation 6.5 is different from the reward the robot provides to the infant. The former is used to learn a policy by RL to regulate the threshold θ that best fits the infant, while the latter is used to motivate the infant every time the infant exceeds the current threshold.

6.5 Experimental Design

This section presents the experimental results collected from the use of the proposed approach in the learning of four different infants.

6.5.1 Procedure Design

In this section, two studies have been conducted namely study 1, and study 2. The four infants have taken part of both studies. The difference between these two studies is that the first one used a fixed reward threshold, $\theta = 3.0m/s^2$, while the second uses the policies learned by the RL approach (Section 6.4.2) to adapt the reward threshold θ. In particular, the contingency phase in study 2 is divided into 20 chunks or steps and the policies are used to determine the threshold θ for each step. Such a policies are pre-trained first on simulation during 50 episodes of 20 steps for each of the infants as described in our previous study [Pulido et al. 2018]. In this way, learning with the real infant begins with an already initialized Q-table, which facilitates a faster convergence to the optimal policy. This initialization is particularly interesting in this context, since learning from scratch would require many experience tuples gathered from the robot-infant interaction to learn an optimal policy, but obtain such amount of experience is unfeasible when we consider real infants. In fact, in the experiments in Section 6.5.2 with real infants, a single 20-step episode has been designed due to the difficulty of recruiting and keeping the babies engaged with the task. It is also important to bear in mind that the babies in this study should be the same as those who participated in study 1, since their collected data are essential to initialize the models for the second study. This implies the need to recruit the participants in a short interval of time, in which their development has not changed much.

The four selected participants were able to finish the session without significant incidents. After analyzing the previous data collected from the four participants, the following levels of difficulty were obtained by applying the methodology explained in Section 6.4.2. The parameter setting is as following. Γ sets for each infant are:

- $\Gamma_{TD1} = \{3.5, 5.9, 10.3, 18.5, 39.4\}$
- $\Gamma_{TD2} = \{3.5, 5.5, 9.4, 16.3, 30.4\}$
- $\Gamma_{TD3} = \{3.5, 5.7, 9.8, 16.2, 26.1\}$
- $\Gamma_{TD4} = \{3.2, 4.2, 6.0, 9.0, 11.6\}$

For the experiments we use the Q-Learning algorithm with $\alpha = 0.4$ and $\gamma = 0.9$, as the most experimentally appropriate values.

6.5.2 Results

Figure 6.4 (a) shows the evolution of the reward threshold values during the 20 chunks of study 2. It shows the average results with their standard deviations of the four infants. Figure 6.4 shows how learned policies begins establishing a threshold low, mid-low, and as the infants learn the contingency, the value of the threshold is adjusted to increasing values. This is because the learned policies are adjusting θ to encourage the infant to gradually increase the acceleration of each movement. The threshold reaches its maximum value around the chunk 14. Interestingly, from this point on the threshold starts a slight decrease. From this point, the policies are being readjusted to lower threshold levels since, at the end of the session, the infants are not able to overcome such high thresholds. In this way, study 2 ends with a mid threshold value, although it can be seen clearly that the trend of the threshold in this study is ascending.

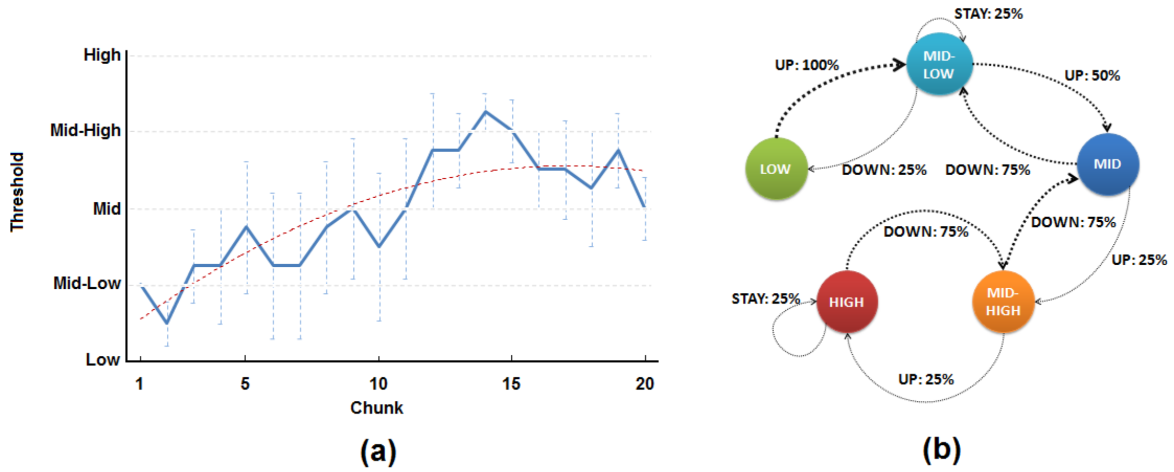


Figure 6.4: a) Evolution of the reward threshold θ during the study 2, and b) graphical representation of the learned policies when the infant is engaged.

Figure 6.4 (b) shows the graphical representation of the adaptation policies learned by RL for each infant. The nodes in the graph represent the states when the infant is engaged with the task, i.e., $\xi = 0$. The arcs show the percentage of times that an action is chosen as the best action in that state, i.e., as the action with the highest Q-value. Thus, if we consider the infants starts in state “Low” (green node in Figure 6.4 (b)), the best action in this state in all cases, i.e., for 100% of infants, is “Up”. This means that all infants are able to overcome the threshold “Low”, hence, the best policy learned in this state is to increase the threshold to “Mid-Low” (light-blue node). In state “Mid-Low”, 25% of policies select the action “Stay” as the best action, 25% of them select “Down” as the best action, and the remaining 50% select the action “Up”. It means that 50% of the infants are able to overcome the “Mid-Low” threshold, while the remaining consider that this threshold is adequate and choose to stay on it or would like a lower threshold. A similar analysis can be made with the other states. At the end, it can be seen how only 25% of the policies choose to increase the threshold to “High” (red node), since reaching and staying in this state requires the infant hits the ball above the maximum threshold. In any case, the graphical representation in Figure 6.4 (b) demonstrates how each infant has learned its own threshold adaptation policy, and how such a policy guides the infant to the state, i.e., to the threshold level, that best fits with his situation at that moment.

However, do these adaptation policies produce improvements with respect to fixing a threshold during all the contingency phase? Figure 6.5 shows the percentage of peaks of acceleration that occurs at each threshold level for studies 1 and 2. From Figure 6.5 it can be seen that 70% of the acceleration peaks in study 1 occur at levels "Low" (40%) and "Mid-Low" (30%). However, only 30% occurs at the highest levels "Mid" (18%), "Mid-High" (7%) and "High" (5%). In fact, the higher the acceleration level is, the lower the number of peaks will be. In contrast, in study 2, 58% of the accelerations occur at levels "Low" (29%) and "Mid-Low" (29%), while the remaining 42% occur at the highest levels "Mid" (20%), "Mid-High" (12%) and "High" (10%). From the evaluation of these results, it can be seen study 2 produces a larger percentage of accelerations at the highest levels "Mid", "Mid-High" and "High" than in study 1 (42% vs 30%), i.e., infants hit the ball with higher accelerations in study 2 than in study 1. In fact, if only the highest level of acceleration "High" is considered, study 2 produces twice as many peaks of acceleration in this study as in study 1 (10% vs 5%). Therefore, results in Figure 6.5 demonstrates the infants have correctly learned the contingency.

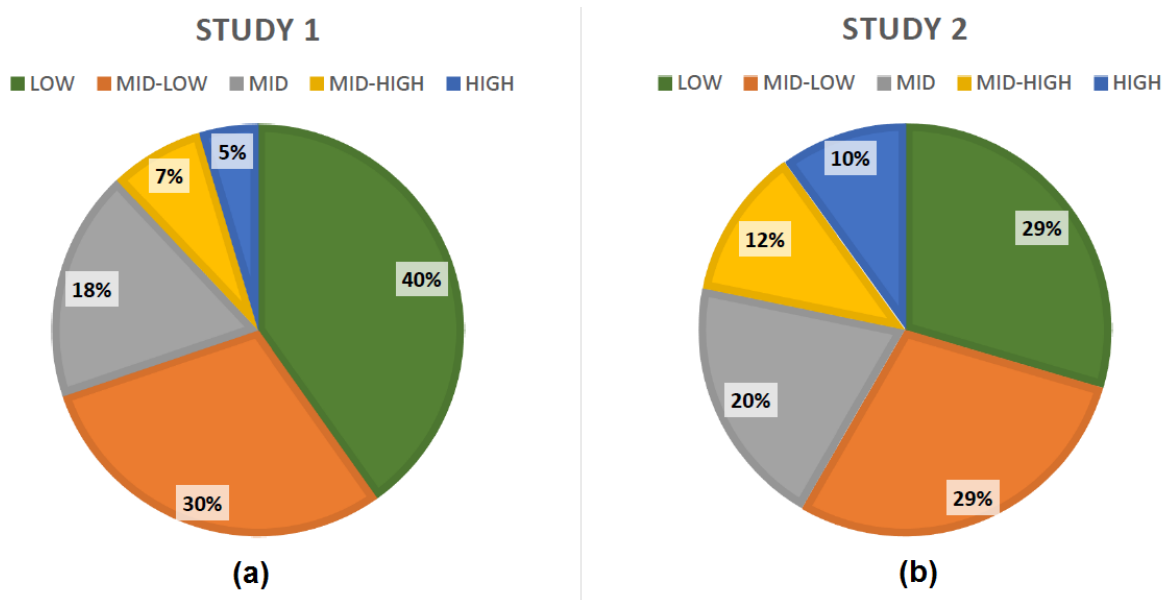


Figure 6.5: Percentage of peaks of acceleration that occurs at each threshold level for studies 1 and 2.

Finally, Table 6.2 reports the number of peaks of acceleration per minute for each infant in studies 1 and 2. Column *Peaks/min* in Table 6.2 demonstrates that the learned policies motivate the infants to also increase the number of peaks per minute with respect to study 1. In fact, Table 6.2 shows an improvement of 41% in Peaks/min in study 2 with respect to study 1. Therefore, in view of all these results, definitively the adaptation policies used in study 2 promotes higher accelerations and a larger number of peaks per minute than the fixed threshold values used in study 1.

Infant	Peaks/min	
	Study 1	Study 2
TD1	45	53
TD2	31	57
TD3	27	47
TD4	51	63
Mean ± Std	$\mathbf{38.5 \pm 11.3}$	$\mathbf{55.0 \pm 6.7}$

Table 6.2: Number of peaks per minute for study 1 and 2.

6.6 Conclusions

This work presents an early approach using RL techniques to deal with the difficulty adaptation problem in infant contingency studies. The model is able to determine the best threshold configuration in terms of peak acceleration of the infant. In particular, the policy learned for each user indicates the thresholds that would reach higher rewards values. Since the reward function is related to the average of the acceleration peaks and the number of peaks detected, it means that maintaining these thresholds in a session would help maximize these two variables. The preliminary results in four infants are very promising. As a result of the use of these policies, infants have been able to learn a more difficult contingency: they have not only learned to make movements, but also to change the acceleration of these movements to continue obtaining robot rewards as demonstrated in Section 6.5. Therefore, the robot is able to encourage the infant to reach higher accelerations from their movements to get better rewards from the robot.

Furthermore, the proposed study clearly demonstrates that the adaptation of the threshold promotes higher accelerations and a larger number of peaks per minute than with typical approaches based on fixed activation thresholds. In general, it is not desirable to have a fixed threshold for all infants since a bad choice of this threshold value can produce some infants to be over rewarded, and others never to be rewarded. Results in Section 6.5 demonstrate that this threshold must be adjusted during learning through strategies that take into account the infant's ability and status.

Finally, it is important to be aware of the fact that this work establishes the basis of a line of research that can be greatly extended. Thus, in the immediate future, it is planned to explore new reward functions that reinforce other aspects of the exercise or even allow the dissociation of one limb from the others.

Chapter 7

Conclusions & Future Lines

This chapter concludes with the latest thoughts of this thesis. Section 7.1 presents the general conclusions of all the conducted studies, as well as the new needs detected and lines of future work, in Section 7.2. The main contributions related to this thesis are chronologically ordered in the Section 7.3, and Section 7.4 presents the awards that recognized the NAOTherapist project during the course of the thesis.

7.1 Conclusions

The main objective of this thesis was to **define and evaluate child-robot interaction models and frameworks, as well as other methodological elements for non-contact robotic rehabilitation to augment pediatric interventions**. For this, an analysis of the state of the art of the four foundations has been made, identifying those aspects that contribute to the domain of neurorehabilitation. Efforts to collect information have been made around: A) the potential gap in neurorehabilitation procedures based on physical therapies and early stimulation, B) how SAR platforms are able to cover this gap while improving clinical interventions, C) the application of gamification in therapeutic environments and D) robot autonomy for both the control of the interaction and the user adaptation.

Based on the information gathered from literature, the fundamental aspects of the four areas have been identified in an attempt to integrate these elements into the framework design: neurorehabilitation, socially assistive robotics, gamification and artificial intelligence. The main challenge is to ensure patient adherence. However, the overexposure to a social robot may cause the patient to become accustomed losing the perception of novelty. The gathered experience together with the literature support the use of gamification as a motivational incentive. Therefore, a framework for the creation of gamified therapies based on SAR has been designed. Pediatric patients have more challenging demands than other individuals, so according to this requirements, an interaction model has been designed based on effort-reward paradigms, named R^3 cHRI model. All this is finally integrated into a general child-robot interaction framework for non-contact rehabilitation.

From this framework, the first prototype called NAOTherapist, focused on physical rehabilitation therapies, is developed. NAOTherapist aims at the design and development of an autonomous robotic prototype to support the rehabilitation of children with Obstetric Brachial Plexus Palsy and Infantile Cerebral Palsy [González et al. 2017]. The system incorporates a NAO robot as the social interactive entity and a RGB-D sensor to monitor the users' movements. The NAOTherapist use case is based on the R^3 cHRI model as well as the involvement of gamification elements such as immersion by storytelling and personalized rewards. Autonomy is a key aspect, so a cognitive robotic architecture was designed using automatic planning for the robot decision making. The system has user adaptation systems based on expert knowledge for automatic adjustment of the difficulty of the exercises. It has been developed to be expert friendly, giving health professionals the opportunity to adapt each treatment to every patient. The system incorporates positive reinforcements that motivate and guide the patients during their treatment, improving the adherence of these to the therapy. For enhancing the prototype, a user-centered prototyping was applied, so improvements are incorporated responding to the user's needs that arise in each of the evaluations.

In order to demonstrate the feasibility of the designed framework, NAOTherapist platform was initially evaluated in two phases [Pulido et al. 2017]: the first phase was carried out with 117 typically developing children to measure the degree of interaction and improve the autonomy of the prototype in accordance with the ongoing requirements. [1] Without any prior explanation, typically developing children were able to follow the session and they mostly considered the robot as a social entity being actively engaged throughout the activity. After that, in a second phase, three pediatric patients from the Virgen del Rocío University Hospital (VRUH) had a first experience with NAO and shared their impression of the usefulness of the NAOTherapist prototype. [2] They enjoyed the activity and were delighted to participate in future

[1] Video of the NAOTherapist use case: https://youtu.be/75xb39Q8QEg
[2] Videos of the 2nd evaluation: https://goo.gl/ZtfrVQ

evaluations. In both phases, participants were able to follow the sessions with the instructions from the robot. The autonomy was considered a key point: making the robot taking its own decisions, improved the perception of the social entity. We also detected the need to create a reward system that would reinforce the patient for every well-done exercise, which would be later a key factor in maintaining patients engaged with the treatment. After this previous experience, these elements were taken into account in improving the architecture.

NAOTherapist robotic platform was validated in two clinical settings: by carrying out a long-term study in the clinical facilities of the VRUH [Pulido et al. 2019], and in an intensive bimanual therapy camp at the UEM. In the first clinical study, 8 pediatric patients were recruited for a 4 month evaluation. The participants were assessed in three different stages by administering clinical scales and satisfaction and usability questionnaires. According to the clinical scales, some patients presented a slight improvement in their motor skills after their training with the robotic platform. This was especially evident in those patients who attended all scheduled sessions. In relation to the evaluation of the acceptance of the technology, patients, relatives and health professionals consider it very useful, easy to use and with correct operation. Relatives in general consider patients to be more motivated to attend the hospital when having sessions with the robot. In all cases, the sessions with the robot provided a greater motivation to the patient compared to the conventional treatment, getting patients to exceed the objectives marked by the therapists and increasing the number of repetitions. The therapist in charged of running the experiments highlighted the ease of its deployment and use of the tool. Despite the duration of the experiment, all the sessions ended correctly without significant incidents. In the same way, the need to create new activities aimed at working on more functional aspects was discussed with the rest of the health professionals. They also detected the need to expand and customize the catalog of rewards: dances, animations, storytelling, and more; which in their opinion was crucial on keeping them engaged throughout the treatment. In relation to the pose adaptation, although the system generally avoided the patients' frustration, its improvement has been projected as future work, towards a more precise adaptation system which considers each articulation in an individualized way with a more sophisticated decision making.

The NAOTherapist platform was also evaluated at the HABIT intensive therapy camp for patients with cerebral palsy. Among the participants, there were 10 patients between 6 and 12 years old and 14 clinical professionals. NAOTherapist participated for 11 consecutive daily sessions offering game-like activities to patients. A total of 110 sessions were carried out without any incident. The system was highly improved since it would be evaluated in an environment of maximum demand [Estévez et al. 2017]. When having daily sessions, patients had to be engaged throughout the study. Game mechanics were included as narrative immersion and new game-like activities. 110 clinical sessions and more than 220 questionnaires were administered and analyzed. Objective perception data demonstrated that 90% of patients improved in the robotic activities. In summary, the results were very promising in terms of usability, social acceptance, user experience and societal impact.

From the technological point of view, the contribution to SAR is very powerful being the highlights of the system: A) the degree of autonomy of the robot, B) hardware independence being able to easily integrate any new robot, sensor or device, C) sessions that include powerful game mechanics improving the concentration, participation and motivation of the patient, and D) an easy target user extensibility to new user needs. This means that the modular design of the core software allows to include new pathologies with low development costs. In relation to the perception system, a 3D sensor calculates clinical metrics up to 50 times per second for accurate clinical reports and data analytics. This active robot collaboration is a labor-saving factor and allows the therapy supervision process to be automated. Thanks to this autonomy, a parallelization of the sessions is expected, so that the therapist-patient ratio may increase, saving a significant cost in high intensity sessions.

Additionally, it is important to note that many of the related SAR platforms for physical rehabilitation have not had experience with patients in clinical settings, and those that had it, were a proof of concept that was not continued. In addition, most of them lack autonomy and do not integrate motion tracking and patient monitoring systems. NAOTherapist platform is a non-contact motor rehabilitation system that has been extensively evaluated and progressively enhanced in different evaluation episodes with very promising results. The first insights reveal the utility and feasibility of the proposed framework for its use in pediatric neurorehabilitation interventions: 1) the system conforms to the clinical guidelines fulfilling the proposed objectives, 2) the robot as a social communication interface guarantees an active engagement improving the experience of the interventions, 3) the integration of immersion mechanisms and rewards encourage the motivation of the patients, improving the adherence to the treatment, and finally, 3) the cognitive architecture has proven to be enough autonomous and robust to face the clinical practice relieving the workload of healthcare professionals.

7.2 Future Lines

This thesis has always pursued a very ambitious goal: the implementation of the SAR-based rehabilitation framework in clinical practice as a routine process. The potential of the developed technology is evident and, given its versatility, it is easily adaptable to other areas of application. This is one reason why this project is still so active after 5 years. That is why, although this thesis establishes the foundations and a functional prototype widely evaluated, there are still some lines of research to be carried out:

- From the technical point of view, improvements are projected around patient adaptation systems for long-term scenarios. The current approach, based on expert knowledge, can be greatly improved by using machine learning and including a greater number of configurable parameters. In the same line, it is also considered of great interest to integrate adaptation models for the specificity of the feedback offered by the robot, that is, the robot must be able to automatically adapt the visual and verbal cues offered to the patient during the sessions. Graded Cueing is a probabilistic technique that some authors use to address this problem [Greczek et al. 2014], and that it may be interesting to explore in order to improve the quality of the feedback offered to the patient.

- In relation to the user motion tracking of the system, currently, a verification of static postures adopted by the users is made. However, the possibility of recognizing complete movements is a very interesting aspect. Although the recognition of activities is a line that began to be explored in this thesis, this idea has not been incorporated in a use case. The initial developed approach used firstly *Clustering* to group the key poses that conform the movement [Jain 2010]. Then, the transitions between these poses were learned using a *Hidden Markov Model* that finally returns the generated movement [Duong et al. 2005]. The main motivation to introduce an activity recognition system is the need to work functional tasks with patients. This would allow to recognize movements based on daily activities, such as brushing teeth, which would benefit the patients' wellbeing to a greater extent.

- Although the engineer's participation has been removed during the configuration and the execution of the therapy, there is still a need to develop new activities. In order to increase the catalog of exercises, an expert in the system is still required to model new activities. Therefore, a very promising line of research is to bring the modeling task closer to health experts. For this, a graphical interface can be integrated to facilitate for clinicians the creation of activities. This interface should integrate a declarative model that translates high-level information into automatic planning PDDL domains [Fox et al. 2003]. The integration of an application of these characteristics would drastically increase the number of possible applications, allowing health experts to develop their own exercises without the need of engineers.

- Regarding the activity, the platform has focused mainly on the motor aspects of neurorehabilitation for the pediatric patient. However, the possibilities of the proposed framework go much further, both from its area of application and the target patient. The system, as designed, could intervene in procedures with patients with autism, diabetes, education of healthy habits, accompaniment in pediatric oncology, and so on, responding to almost any identified need in healthcare [Breazeal 2011]. Also, its application in the elderly is practically direct to treat dementia or even active aging [Fasola et al. 2013]. The author of this thesis considers very promising the idea of parametrizing the robotic sessions so that they can be directed to any audience, that is, to be able to personalize the speech, the activity, rewards, interaction flow, pace, times, etc. Of course, this would be a derivation of this project completely, diversifying the final system in different segments of stakeholders. This is the most ambitious goal, bringing this platform much closer to patients and therapists demands and other evaluation areas. Because the most important thing is that the results of this thesis can be used by anyone and from anywhere.

7.3 Contributions

JCR JOURNAL

- **A Socially Assistive Robotic Platform for Upper-Limb Rehabilitation: A Longitudinal Study With Pediatric Patients:** JC. Pulido, C. Suarez-Mejias, JC. Gonzalez, A. Dueñas, P. Ferrand, M.E. Martinez, C. Echevarria, P. Infante-Cossio, C. Luis Parra and F. Fernandez. *IEEE Robotics & Automation Magazine (IEEE RAM)*, vol. 1, pp. 1-16, IEEE April 2019, **JCR 2017 impact 3.573 – Q1**, doi:10.1109/MRA.2019.2905231.
- **Socially Assistive Infant-Robot Interaction: Using Robots to Encourage Infant Leg-Motion Training:** N. Fitter, R. Funke, JC. Pulido, L. E Eisenman, W. Deng, M. R Rosales, N. Bradley, B. Sargent, B. Smith, M. J Mataric.
2019 *IEEE Robotics & Automation Magazine (IEEE RAM)*, vol. 1, pp. 1-16, IEEE April 2019, **JCR 2017 impact 3.573 – Q1**, doi:10.1109/MRA.2019.2905231. (USC)
- **Developing a Robot-Guided Interactive Simon Game for Physical and Cognitive Training:** Mısra Turp, José Carlos González, José Carlos Pulido and Fernando Fernández. *International Journal of Humanoid Robotics (IJHR)*, vol. 19(1), p. 195003, World Scientific, February 2019, **JCR 2017 impact 0.908 - Q4**, doi:10.1142/S0219843619500038.
- **Evaluating the Child–Robot Interaction of the NAOTherapist Platform in Pediatric Rehabilitation:** José Carlos Pulido, José Carlos González, Cristina Suárez-Mejías, Antonio Bandera, Pablo Bustos and Fernando
2017 Fernández. *International Journal of Social Robotics (IJSR)*, vol. 9(3), pp. 343–358, Springer, June 2017, **JCR 2017 impact 2.003 - Q3**, doi:10.1007/s12369-017-0402-2.
- **A three-layer planning architecture for the autonomous control of rehabilitation therapies based on social robots:** José Carlos González, José Carlos Pulido and Fernando Fernández. *Cognitive Systems Research (CSR)*, vol. 43, pp. 232-249, Elsevier, June 2017, **JCR 2017 impact 1.425 - Q3**, doi:10.1016/j.cogsys.2016.09.003.

WORKSHOP AND CONFERENCE

- **Adaptation of the Difficulty Level in an Infant-Robot Movement Contingency Study:** José Carlos Pulido, Rebecca Funke, Javier García, Beth A. Smith and Maja Matarić, on the *3rd Iberian Robotics Conference, (ROBOT 2017), on in proceedings of the 19th Workshop of Physical Agents (WAF), pp. 70-83, Madrid (Spain), November 2018*. (USC)
2018
- **Classifying Infant Motor Development using Day Long Movement Data from Wearable Sensors:** David Goodfellow, Ruoyu Zhi, Rebecca Funke, Jose Carlos Pulido, Maja J. Mataric, Beth A. Smith, on the 2018 KDD Workshop in Machine Learning in Healthcare and Medicine, London (UK), August 2018. (USC)
- **Enhancing a Robotic Rehabilitation Model for Hand-Arm Bimanual Intensive Therapy:** Enrique García
2017 Estévez, Irene Díaz Portales, José Carlos Pulido, Raquel Fuentetaja and Fernando Fernandez, on the *3rd Iberian Robotics Conference, (ROBOT), Rehabilitation and Assistive Robotics special session*, Seville (Spain), November 2017.
- **NAOTherapist: Autonomous Assistance of Physical Rehabilitation Therapies with a Social Humanoid**
2016 **Robot:** José Carlos Pulido, José Carlos González and Fernando Fernández, in proceedings of the International Workshop on Assistive & Rehabilitation Technology (IWART), pp. 15-16, Elche (Spain), December 2016.
- **Playing with Robots: An Interactive Simon Game**: Mısra Turp, José Carlos Pulido, José Carlos González, Fernando Fernández, in *proceedings of the Workshop on Social Robotics and Human-Robot Interaction (RSIM)*, *CAEPIA 2015* Albacete (Spain), 2015.
- **Therapy Monitoring and Patient Evaluation with Social Robots**: Alejandro Martín, José Carlos González,
2015 José Carlos Pulido, Ángel García-Olaya, Fernando Fernández and Cristina Suárez-Mejías, in *proceedings of the 3rd Workshop on ICTs for improving Patients Rehabilitation Research Techniques*, *REHAB 2015* Lisbon (Portugal), 2015.
- **Planning, Execution and Monitoring of Physical Rehabilitation Therapies with a Robotic Architecture**: José Carlos González, José Carlos Pulido, Fernando Fernández and Cristina Suárez-Mejías, in *proceedings of the 26th Medical Informatics Europe conference (MIE)*, *Studies in Health Technology and Informatics*, vol. 210, pp. 339-343, Madrid (Spain), 2015.
- **Goal-directed Generation of Exercise Sets for Upper-Limb Rehabilitation**: José Carlos Pulido, José Carlos
2014 González, Arturo González-Ferrer, Javier García, Fernando Fernández, Antonio Bandera, Pablo Bustos and Cristina Suárez, in *proceedings of the 5th Workshop on Knowledge Engineering for Planning and Scheduling (KEPS)*, ICAPS conference, pp. 38-45, Portsmouth (New Hampshire, USA), 2014.

* USC symbol refers to the studies carried out during my international internship at the Interaction Lab of the University of Southern California.

7.4 Awards and Media Impact

The NAOTherapist project has been awarded numerous prizes throughout its development, both as a health innovation project and as an entrepreneurial business proposal.

Various media have echoed the project, appearing on television, magazines and newspapers. Especially highlights the participation in a documentary of National Geographic, where NAOTherapist is the main protagonist [3].

[3]NATGeo video: https://youtu.be/1VuEiSbdpRA

Appendix A

Evaluation of Therapy Designer

The automatic generation of therapies is addressed in a hierarchical way and belongs to the higher level of the architecture. In order to evaluate the performance of the HTN model, the JSHOP2 planner [Nau et al. 2003] was used for the experimentation, running in a PC with the following configuration: Intel Core i3, 3.30GHz x 4, 8 GB of RAM. The first evaluation tries to demonstrate the performance of the therapy designer module in terms of planning time while increasing the complexity of the problems (Table A.1). The second evaluation focuses on the therapeutic significance of the planned sessions. There are two experiments that validate, firstly the order of the exercises in the sessions under the clinical and variety criteria (Table A.2), and secondly the obtained average distribution of the intensity and difficulty throughout the sessions (Figure A).

		Number of sessions					
		2	5	10	20	50	100
Exp. A	Blind	1.50	1.74	2.70	4.74	13.21	30.75
	Heuristic function	1.20	1.44	2.50	4.36	10.65	25.86
Exp. B	Blind	1.02	8.66	>1800	>1800	>1800	>1800
	Heuristic function	1.01	1.86	2.66	6.46	18.09	764.08

Published in [González et al. 2017]

Table A.1: Planning time in seconds, facing the blind selection against the proposed heuristic function for both (A) relaxed and (B) tightly-adjusted experiments.

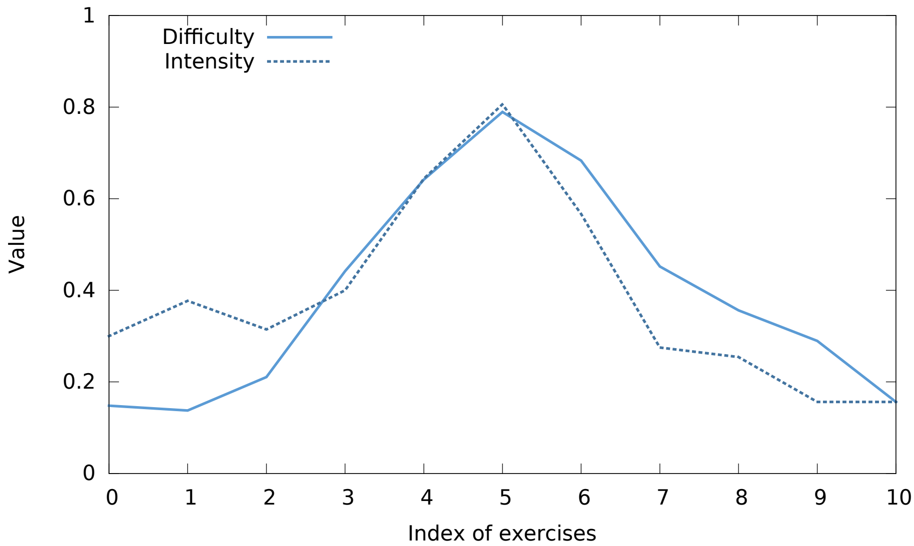
The planning process has three main goals: reaching the cumulative levels established by physicians (TOCLs), ensuring the variability of occurrences of exercises and respecting the time limits of the session. The planning time is very dependent on the relationship between the TOCLs and time constraints. This means that problems with tightly-adjusted values require more time to find a suitable combination of exercises which achieves the TOCLs for the established session time. For this reason, two different configurations were evaluated to determine the performance of the heuristic function in contrast to the blind selection of exercises. It should be pointed out that blind policy is a circular selection by default in the planner. It is expected that the informed heuristic function reduces the number of inefficient bindings which may cause too many backtracks, affecting the performance.

Sessions	**Exercises**																	
S1	e18	e19	e25	e26	e1	e11	e31	e29	e30	e17	e3	e10	e16	e4	e7	e9	e15	e6
S2	e12	e6	e22	e18	e0	e29	e30	e31	e8	e13	e14	e11	e17	e3	e9	e15	e27	
S3	e19	e22	e28	e25	e31	e2	e10	e16	e7	e8	e13	e14	e11	e9	e15	e12		
S4	e18	e19	e26	e27	e28	e1	e17	e20	e21	e24	e4	e3	e10	e16	e23	e22	e9	
S5	e6	e12	e18	e19	e25	e31	e5	e7	e8	e13	e14	e10	e3	e4	e9	e15	e22	
S6	e26	e27	e28	e25	e2	e0	e20	e31	e16	e3	e10	e4	e17	e11	e15	e6	e12	
S7	e18	e19	e26	e27	e28	e2	e11	e21	e20	e16	e4	e3	e10	e5	e22	e9	e15	e6
S8	e12	e6	e18	e19	e25	e31	e0	e8	e7	e14	e13	e16	e3	e10	e9	e15	e22	
S9	e26	e27	e28	e25	e1	e5	e21	e31	e29	e30	e16	e17	e7	e12	e6	e9		
S10	e18	e19	e26	e27	e28	e1	e17	e11	e8	e3	e10	e16	e13	e14	e7	e12	e15	e6
S11	e22	e18	e25	e26	e2	e11	e31	e29	e30	e20	e21	e24	e23	e19	e27	e28		
S12	e12	e6	e22	e18	e0	e29	e30	e31	e13	e8	e14	e17	e7	e9	e15	e25		
S13	e19	e22	e26	e27	e1	e17	e31	e20	e21	e5	e0	e4	e3	e10	e9	e15	e23	
S14	e28	e12	e6	e19	e20	e30	e11	e8	e14	e13	e7	e3	e16	e9	e15	e22		
S15	e18	e19	e25	e26	e5	e8	e29	e30	e31	e21	e20	e10	e4	e22	e9	e15		

Published in [González et al. 2017]

Table A.2: Distribution of the exercises of 15 executed sessions with the same session objectives. The color of the cells represents the three phases of training: green for warm-up, yellow for training and blue for cool-down.

Table A.1 shows the results in seconds facing both selection policies while increasing the number of sessions to be planned. This was tested with 70 exercises in the knowledge base. Experiment A was carried out with a relaxed configuration of the problem. This means that TOCLs were low with respect to time constraints and exercises available. Although the time of the heuristic selection is low, the differences are not very significant. However, experiment B shows completely different results when the TOCLs are tightly adjusted. In this situation, the blind selection needs to try so many bindings to find a set of exercises that meets the established criteria. From the generation of 10 sessions, the time was more than 1.8 seconds which is hardly acceptable when a quick response is expected.



Published in [González et al. 2017]

Table A.2 aims to show the distribution of 15 planned sessions with 70 exercises from the knowledge base. The session was configured with a duration that ranges from 25 to 30 minutes. The table has colored cells to represent the three phases that comprise a session (warm-up, training and cool-down). As can be seen, the penalty for repetition included in the heuristic function allows a variety of exercises between sessions and avoid cycles. The model also prevents the repetition of exercises in one session or in the same position as the last occurrence. In this case, since there are enough exercises, the model does not need to suggest new exercises, so that the planner is able to find a varied distribution of exercises that reaches the established therapeutic goals (TOCLs).

In order to evaluate the intensity and difficulty distribution, a problem with 72 exercises was solved with JSHOP2 with the following configuration: 30 sessions of 25-30 minutes each, 40% of the session time was divided evenly into warming up and cooling down and the remaining 60% was spent on the training phase. Those exercises whose intensity and difficulty are between 0 and 0.4 are considered by the model as warm-up or cool-down exercises, but when these values are greater than 0.4, they can be included in the training phase. The average intensity and difficulty value with respect to the index of exercises of the generated plans is shown in Figure A, where both distributions approximate a desired Gaussian-like function. With the aim of providing a customized shape of the function, the model considers that exercises can be more intense but less difficult in the warm-up phase and vice versa for the cool-down phase.

Appendix B

Episode 1: Evaluation Questionnaires

B.1 Children's Questionnaire

Q1. Was it easy to understand what to do with the robot?
Q2. Do you think the robot is alive?
Q3. Do you think the robot was gazing at you?
Q4. Did you feel overwhelmed when the robot talked to you?
Q5. Do you think the robot speaks too much?
Q6. Do you think the robot has feelings?
Q7. Choose 5 adjectives to describe the robot
Q8. What name would you give to the robot?
Q9. How old do you think the robot is?
Q10. Would you like to have this robot at home?
Q11. Would you like to be treated by the robot?
Q12. Do you think the robot can see you?
Q13a. Do you think the robot can hear you?
Q13b. Do you think the robot is glad when you play together?
Q13c. Would you like to do more exercises with the robot?
Q13d. Which games would you want to play with the robot?
Q15. Did the robot correct an actual correct pose?
Q16. Which exercise did you like most?
Q17. Which exercise was the most difficult?
Q18a. Did you understand the descriptions of the exercises?
Q18b. Were the exercises tiring?
Q18c. Did the lights of the eyes help you to do the exercises?

Q19a. Were the exercises boring?
Q19b. Why?

B.2 Observers and Experts' Questionnaire

Q1. Did the child understand what to do?
Q2. Are the movements of the robot natural?
Q3. Did the child perform the movements naturally?
Q4. Was the child overwhelmed during the session?
Q5. Did the robot correct an actual correct pose?
Q6. Was the session carried out fluently?
Q7. Was the child very committed to the session?
Q8. Was this experience beneficial for the child?
Q9. Did the child make a great effort to finish the session?
Q10. Is this system a useful tool for physiotherapy?

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